SPACECRAFT MICRO-VIBRATION: A SURVEY OF PROBLEMS, EXPERIENCES, POTENTIAL SOLUTIONS, AND SOME LESSONS LEARNED

Cornelius Dennehy [(1)], Oscar S. Alvarez-Salazar [(2)]

[(1)] NASA Technical Fellow for GN&C, NASA Engineering and Safety Center (NESC), NASA/Goddard Space Flight Center, Greenbelt, Maryland 20771, USA, Email:cornelius.j.dennehy@nasa.gov:
[(2)] Oscar S. Alvarez-Salazar, JPL Principal Engineer for GN&C, GN&C Control Analysis Technical Group, Jet Propulsion Laboratory (JPL))/California Institute of Technology, Pasadena, California 91109, USA, Email: oscar.s.alvarez-salazar@jpl.nasa.gov

ABSTRACT

Predicting, managing, controlling, and testing spacecraft micro-vibrations due to on-board internal disturbance sources is a formidable multi-disciplinary systems engineering challenge, especially for those observatories hosting extremely sensitive optical sensor payloads with stringent requirements on allowable Line-of-Sight (LOS) jitter. In this paper some specific spacecraft micro-vibration engineering challenges will be introduced and described. Technical background context is provided with the inclusion of several illustrative examples of NASA and ESA missions (both past and present) where dynamic interactions have to be addressed and which have demanding payload instrument LOS jitter requirements. A general modeling, analysis, simulation, and test approach to address and solve the overall problem of spacecraft micro-vibrations is outlined. Recommended rules of thumb are presented to provide guidance for analysts on where to initiate and how to approach a new spacecraft micro-vibration design problem. A set of experience-based spacecraft micro-vibration lessons learned are also presented in the hope they can be leveraged on new system development projects to help overcome unfamiliarity with previously identified micro-vibration technical pitfalls and challenges.

1. INTRODUCTION TO THE MICRO-VIBRATION PROBLEM

In the formulation of their next generation of Space and Earth science missions, there is a constant trend by both National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) to push towards higher performing payloads and instruments. This manifests itself in increasingly demanding requirements for science/observational instrument resolution, pointing stability, lower sensor operating temperatures, etc. The trend with more capable systems will generally be towards increased detector resolution and sensitivity, sometimes leading to greater dwell time, usually leading to tighter pointing requirements. Next generation imaging system requirements for increased Focal Plane Array (FPA) resolution and longer integration time can directly drive associated requirements for higher instrument pointing stability and allowable Line-of-Sight (LOS) jitter. Likewise, the need for operating instruments and sensors at much colder operating temperatures will likely drive a need for on-board cryocoolers that will introduce pointing disturbances.

Both NASA and ESA are currently planning spaceflight missions that include high-performance optical payloads with highly vibration-sensitive scientific/observational instruments. The types of missions included here span both space science and Earth observation applications. Control of micro-vibrations is also critical for stabilizing optical communications payloads, another very demanding mission application. Often the goals and objectives of these missions result in rigorous and challenging requirements on the design of the observatory (i.e., the spacecraft bus plus the optical payload) to provide precise bus pointing and mechanically quiet science instrument accommodations in the face of dynamic interactions.

In particular, these instrument accommodation requirements often manifest themselves as very stringent, arcsecond (arcsec) level or less, constraints on attitude stability and rate stability at the instrument interface with the spacecraft over a vastly extended frequency range well beyond the Attitude Control System (ACS) bandwidth. The inherent lightweight nature of these observatory structures and the resulting multitude of closely spaced, lightly damped, low-frequency flexible body modes of vibration, as well as the variety of higher frequency disturbance sources, make meeting these challenging engineering requirements very demanding. Thus, it is not surprising that the technical challenges associated with understanding, managing, and controlling observatory dynamic interactions which create micro-vibrations have now risen in prominence to form one of the most daunting and critically important spacecraft systems engineering problem areas.

For the purposes of this paper, spacecraft micro-vibrations are small-amplitude mechanical vibrations due to dynamic interactions, usually in the range of micro-g's to milli-g's, which typically occur at frequencies from a few Hz up to a few hundred Hz [1].

Looking back one can observe that both NASA and ESA, together with their industry partners, have a long, technically rich, and impressive history of successfully addressing the spacecraft engineering problems associated with managing undesirable dynamic interactions that perturb an observatory's payload instrument pointing/pointing stability (aka "jitter"). This micro-vibration engineering history can be traced as far back as the mid-1970s when NASA was studying architectural concepts for the so-called Large Space Telescope (LST), which was to later become much better known as the Hubble Space Telescope (HST). Readers with an interest in an insightful historical discussion of spacecraft micro-vibration engineering over the last four decades are directed to [2], where this important history is provided in the form of a detailed and valuable technical literature review. Additionally some excellent discussion into the jitter problem is provided in [3-4] where two different mission perspectives on methods and approaches for managing the spacecraft micro-vibration problem are explained in detail.

Micro-vibrations are generated by internal mechanisms/mechanical devices placed on-board the observatory. These disturbance-generating devices typically include internally rotating mechanisms such as a Reaction Wheel (RW) and/or a Momentum Wheel (MW) which are almost always located on the spacecraft bus. Other micro-vibration sources include payload-generated excitations from sensor cryocoolers and cryopumps, as well as instrument-internal mechanisms such as scanning mirrors, steering mirrors, and filter wheel mechanisms. Disturbances can also arise from the use of High Gain Antenna (HGA) and or Solar Array (SA) drive mechanisms, appendage gimbal drives/pointing mechanisms, and attitude control/momentum dumping thrusters. Propellant sloshing and control-structures interactions may also contribute to the spacecraft's internal disturbance environment and can potentially excite micro-vibration at a critical payload instrument location.

One aspect that makes the spacecraft micro-vibration problem organizationally challenging is the fact that it is a true observatory-level problem involving multiple engineering disciplines: Structures; Mechanisms and Mechanical Systems; Guidance, Navigation and Control (GN&C); Loads and Dynamics; and of course, System Engineering. The micro-vibration modeling and analysis work necessarily overlaps traditional spacecraft subsystem boundaries and requires observatory-level management, cross-discipline communications and overall coordination for mission success. While multiple organizations are typically involved, the leadership in understanding micro-vibration issues usually comes from Systems Engineering, GN&C and/or the Mechanisms and Mechanical Systems technical staff.

Before ending these introductory comments the authors would be remiss if they didn't mention the area of 'micro-dynamics' because, while not the focus of this particular paper, it is an area closely related to micro-vibrations. Thermal distortion of structures can also strain joints and interfaces and if the strain builds enough to "slip" the joint or latch or interface, then an impulsive disturbance will cause misalignment and micro-vibrations in the structure. This can happen in portions of the system exposed to changes in thermal loading like solar shades, SAs, or in systems with low thermal mass exposed to large swings in thermal loading. The community commonly refers, in a collective manner, to such mechanics as 'micro-dynamics'.

2. SOME OBSERVATORY MICRO-VIBRATION EXPERIENCES

The following are some short survey-level descriptions that highlight the various types of experiences relevant to micro-vibrations caused by undesirable dynamic interactions, which occurred on twelve specifically selected NASA and ESA missions.

2.1. Hubble Space Telescope (HST)

The Hubble Space Telescope (HST) observatory, the first of NASA's so-called Great Observatories, was deployed on 25 April 1990 from the Space Shuttle Orbiter Discovery into a 332-nmi Earth orbit. The HST was designed to achieve stringent LOS pointing stability while observing celestial objects for long exposures. At the highest-level, the telescope's pointing requirement was specified at <7 milli-arcsecond (mas) over a 24-hour period.

As described in [5-8], the Pointing Control System (PCS) for this ground-breaking, one-of-a-kind space-based observatory was carefully designed to stabilize the SA and coupled vehicle-telescope bending modes. Not surprisingly significant resources were devoted to performing pre-launch jitter analysis and prediction, much of it focused on disturbance source modeling and characterization to understand the potential impacts on the telescope's LOS jitter. As described in [9], the initial HST jitter studies at the prime contractor, which were based upon historical approaches used by the contractor on classified satellites, were devoted to predicting disturbance effects on an LOS central pointing vector along with minimizing other known image-distorting effects. An additional design goal was to ensure a large separation of the primary structural mode frequencies from the maximum active control bandwidth frequency. The prime contractor also developed a full-scale Structural Dynamics Test Vehicle (SDTV). The SDTV was a medium-fidelity demonstrator assembled with flight-like structural components. In addition, as also described in [9], an unprecedented set of high-sensitivity induced vibration data was acquired for each of the five flight-certified RWs used in the PCS. Ultimately, a Dynamic Interaction Test (DIT) of the full-up HST observatory, suspended by bungee-cord-like devices to off-load gravity, was performed in the prime contractor's test facility to more fully characterize the telescope's susceptibility to micro-vibration disturbances. In order to demonstrate the required level of performance, multiple city blocks around the prime contractor's test facility were effectively shut down from vehicular traffic.

Not long after its on-orbit activation, problems were experienced that severely impacted the HST's capability to perform its mission. Not only was an optical flaw discovered in the telescope's main mirror, but also examination of the real-time flight telemetry data revealed that the HST was experiencing unexpectedly large disturbances that were most pronounced as the spacecraft entered or left the Earth's shadow. A focused effort to investigate the nature of the observed pointing disturbances identified the SAs as the source of the disturbance. The thermal/mechanical energy in the arrays was being stored and released in such a manner as to excite the primary modes of the arrays. The PCS, as initially designed, was unable to compensate for these unexpected pointing perturbations due to the so-called Sunrise/Sunset 'thermal snap' SA disturbances.

As soon as the problem was identified, efforts to redesign the PCS to eliminate the effects of the disturbances began. A successful reconfiguration of the flight computer and redesign of the control system, along with a slight modification of the original performance requirements, resulted in a controller that met the new specifications most of the time. Because of the PCS redesign efforts, a wealth of flight data were collected that was specific to the control system performance. Simulation models were enhanced as more was learned about the on-orbit dynamic behavior of the spacecraft. Techniques were developed to explore the behavior and performance of new controller designs using actual flight data to simulate the disturbances imparted on to HST by the flexible SAs. To take maximum advantage of the data and simulations available, a design study was initiated. The excellent engineering work highlighted above to recover HST pointing performance is described in detail in [10-14].

It should also be mentioned that, in preparation for the insertion of the ingenious Corrective Optics Space Telescope Axial Replacement (COSTAR) device to correct the optical flaw in the telescope's main mirror, NASA performed an enormous amount of very detailed on-orbit jitter characterization testing to reduce risk.

Later in its mission, another HST micro-vibration issue surfaced concerning the pointing disturbance caused by the Near Infrared Camera and Multi-Object Spectrometer (NICMOS) Cryo Cooler (NCC). The NCC is a single-stage reverse Brayton cycle system using micro turbo-machinery to provide necessary cooling to the detectors of the NICMOS infrared science instrument. The NCC was installed in March 2002 during the HST Servicing Mission 3B (SM3B). Ground testing and analytical predictions for HST on-orbit jitter levels after SM3B, with all disturbance sources active, indicated that the NCC would be the predominant disturbance source generating significant jitter for HST. Therefore, as described in [15-16], there was extensive testing conducted to quantify the expected on-orbit disturbances caused by the micro turbo-machinery. This testing provided validated inputs to a flexible body dynamic simulation in order to demonstrate compliance with the HST 7 mas jitter requirement.

2.2. Chandra

The Chandra science observatory was launched in July of 1999. The third of NASA's Great Observatories, Chandra's primary mission is to address some of the most fundamental questions in present-day astrophysics through observations of X-rays. A detailed description of Chandra's Imaging Pointing Control and Aspect Determination System is provided in [17].

The Chandra project team discovered at their Critical Design Review (CDR) that disturbances due to RW imbalance were too large, and determined that the only way to comply with its jitter requirements was to include RW isolation. The passive RW jitter isolation system used to meet the Chandra's imaging performance requirements is described in [18].

The CDR jitter results were a disturbing surprise to the project team since the design margins were healthy until new models for all subsystems were included in the CDR analysis cycle. This experience points to the recognition that inclusion of sufficient uncertainty in analytical predictions is needed to avoid late requirement violations.

2.3. Solar Dynamics Observatory (SDO)

The Solar Dynamics Observatory (SDO) mission has the goal of understanding the changing Sun and its effects on the Solar System, life, and society. The SDO spacecraft carries three Sun-observing instruments to geosynchronous orbit: Helioseismic and Magnetic Imager (HMI), the Atmospheric Imaging Assembly (AIA), and the Extreme Ultraviolet Variability Experiment (EVE). The basic mission of SDO is to observe the Sun for a very high percentage of the 5-year mission (10-year goal) with long stretches of uninterrupted solar observations and with constant, high-data-rate transmission to a dedicated ground station. The SDO mission has very tight pointing jitter requirements for its Sun-observing instrument pointing. Both the AIA and HMI science instruments on SDO are sensitive to high-frequency pointing perturbations and have sub-arcsec level LOS jitter requirements. These stringent mission requirements became design drivers for the observatory in general and for the ACS in particular. A detailed description of the SDO's ACS is provided in [19]. Each science instrument has an Image Stabilization System (ISS) with some ability to compensate for high frequency motion. Below the bandwidth of the ISS the control system itself must suppress disturbances within the ACS bandwidth while also avoiding exciting jitter at higher frequencies.

A jitter analysis activity performed early in the SDO project lifecycle for which the objective was to verify requirements using a preliminary observatory structural finite element model and preliminary RW disturbance models is described in [20]. The results of this early analysis provided the SDO project team a direct comparison of jitter performance using two different candidate RWs. These early results were then employed by project decision makers to technically inform the SDO RW selection process. The results of SDO jitter analysis and modeling efforts are documented in [21].

Another important SDO jitter-related activity was the design of a new pointing algorithm, which mitigated the spacecraft's HGA jitter during the motion of the two HGA antennas during high data rate communications downlink periods. As mentioned above the SDO's science instruments require fine Sun pointing and have a very low jitter tolerance. Analysis showed that the nominal tracking and slewing motions of the antennas could cause enough jitter to exceed the specific portion of the jitter budget allocated to the HGA disturbance. As described in [22] the HGA pointing control algorithm was expanded from its original form in order to mitigate the jitter.

Since, as mentioned above, both the AIA and HMI science instruments on SDO are very sensitive to the blurring caused by jitter, extensive modeling and analysis was performed at the NASA Goddard Space Flight Center (GSFC). To verify the disturbance models and to validate the jitter performance prior to launch, many jitter-critical components and subassemblies were tested either by the mechanism vendors or by NASA GSFC. Although detailed analysis and assembly level tests were performed to obtain good jitter predictions, there were still several sources of uncertainties in the system. The structural finite element model did not have all the modes correlated to test data at high frequencies (>50 Hz). The performance of the instrument stabilization system was not known exactly but was expected to be close to the analytical model. A decision was made that a true disturbance-to-LOS observatory level test would not be performed for multiple reasons: schedule impact, cost, technical challenges in implementing an effective 1-g negation system from which to suspend the SDO spacecraft, and the attendant risks of potentially damaging flight hardware. To protect the observatory jitter performance against model uncertainties, the SDO jitter team devised several on-orbit jitter reduction plans in addition to specifying reserve margins on analysis results. Since some of these plans severely restricted the capabilities of several spacecraft components (e.g., the RWs and HGA), the SDO team performed on-orbit jitter tests to determine which jitter reduction plans, if any, were necessary to implement in order to satisfy science LOS jitter requirements. The SDO on-orbit jitter tests described in [23] were constructed to satisfy the following four objectives: 1) determine the acceptable RW operational speed range during Science Mode, 2) determine HGA algorithm jitter parameters, 3) determine acceptable spin rates for EVE instrument filter wheels, and 4) determine if AIA instrument filter wheels excite the first AIA telescope structural mode.

2.4. Solar and Heliospheric Observatory (SOHO)

The Solar and Heliospheric Observatory (SOHO) spacecraft, a cooperative effort between ESA and NASA, was launched in December 1995 into a halo orbit around the Lagrange Point L1 of the Sun-Earth System. Originally planned as a 2-year mission, SOHO continues to operate today after over 20 years in space and, in November 2016, an extension lasting until December 2018 was approved by mission managers. From its L1 vantage point, SOHO has helped scientists explore different aspects of the Sun's behavior with images taken by the numerous scientific instruments that compose its payload. The SOHO spacecraft was designed to provide the science instruments with LOS stability below their image pixel or resolution requirements. This translated into short-term stability requirements below 1 arcsec for most of the instruments in the payload. The performance objective was to keep the peak dynamic jitter as low as 0.3 to 0.5 arcsec. The micro-vibration problem thus presented to the SOHO team was a challenging one. This was especially true given the limited state in-house experience and knowledge base in the early-mid 1990s for dealing with such a complex observatory. The SOHO jitter assessment study, as described in detail in [24], was formulated as a well-balanced, pragmatic and logical combination of analysis and multiple tests to anchor the models and jitter prediction simulations. A series of modal survey tests on observatory substructures was performed to support the construction of a validated spacecraft structural Finite Element Model (FEM). Component level testing was performed to characterize the individual disturbance sources. The most significant disturbances were identified as the RWs, which are very typical, as well as a number of scanning, focusing, and rolling mechanisms associated with individual science instruments. A SOHO jitter prediction analysis was performed, which supported the project team in the process of working out the appropriate pointing/jitter error budget and proper requirements flow down. A final pre-launch jitter verification DIT test was performed in February 1995 on a representative configuration of the flight model SOHO spacecraft. Similar to most such full-up observatory DITs, the fundamental objective of this test was to make experimental measurements of the jitter induced on the most sensitive instruments by sequential activation of individual "real-world" disturbance sources. The SOHO jitter team was especially interested in obtaining this LOS jitter data at frequencies above 150 Hz, the frequency point beyond which the validity of the spacecraft FEM was believed by the team to be questionable. The SOHO spacecraft was hung in the test facility using a compliant bungee-cord-like suspension system to minimize gravity effects towards the goal of replicating the free-free boundary conditions found in-flight. The jitter test data collected during this suspended DIT correlated well with the analytical predictions with any deviations being explainable. It is noteworthy that the DIT data revealed that the jitter level induced on the payload instruments above 150 Hz was very small for all of the disturbance sources.

As related in [23], the ultimate validation of acceptable in-flight jitter levels was accomplished through the use of a clever micro-vibrations measurement technique. The ISS of SOHO's Michelson Doppler Imager (MDI) contains a relatively high bandwidth electro-mechanical servo-actuator for performing active closed-loop LOS stabilization using a small gimbaled mirror, which is tilted by an angular actuator. SOHO's downlinked telemetry includes a measurement of the servo-actuator current, which is sampled at a 512-Hz rate. Essentially this measurement of this ISS servo current, converted to an angular representation with a threshold of a few tenths of a micro-radian, provides a direct indication of the micro-vibration amplitude as measured at the MDI instrument LOS level. Systematic calibration of the MDI ISS servo signal was done pre-launch during SOHO jitter ground testing and the capability to make these micro-vibration measured was demonstrated in the ground test environment as well. There are limitations on this technique of using the MDI ISS for in-flight micro-vibration measurements however. For example, LOS jitter is measured in-flight only on the MDI, and furthermore it is measured only at some selected RW speeds. As indicated in [23], it is not possible to acquire and downlink the MDI ISS data during a RW spin down. Comparing the in-flight micro-vibration data with pre-launch analytical jitter predictions and with ground test results showed a general positive consistency in the jitter levels. However, in some instruments the in-flight LOS jitter was seen to be much less than predicted by the micro-vibration analysis. Investigations into those discrepancies revealed the cause of the over-predictions to be either the use of worst-case analytical assumptions not actually seen in-flight or less dynamic coupling than assumed in the pre-launch jitter analysis.

Looking back, the SOHO jitter assessment experience appears to have been a very comprehensive and well-constructed campaign from which both ESA and NASA drew some important lessons learned to apply to their future complex and demanding mission applications.

This SOHO experience points to the importance of understanding the observatory's disturbance spectrum (from various sources) and its impact on critical payload elements. Understanding what the effects are on pointing stability and determining if any local payload structure get excited by the disturbances is sometimes only revealed by testing. The spacecraft FEM will usually provide the jitter team with clues with respect to susceptible frequencies, but there is significant uncertainty in how energy is actually attenuated and spread across a given structure. Much of this uncertainty comes from a lack of knowledge concerning energy transmission across structural interfaces and devices such as joints, hinges, and brackets. A physical observatory system-level test to assess dynamic interactions, in which disturbance sources are operated and resulting LOS performance is measured, is an indispensable way to increase the pre-launch understanding of the complex dynamic interactions taking place within the observatory. A comprehensive DIT should be performed over all frequencies of interest, not just those with where the spacecraft FEM is expected to be less valid.

One last comment on the SOHO experience concerns their comparison of pre-launch analytical jitter predictions with the observed in-flight jitter. One would expect that, and in fact should ensure that, the pre-launch analysis is always conservative (e.g., accomplished through the use of conservatively low values of damping and/or the use of more compliant coupling terms) and that the actual in-flight performance should be better than predicted. Which is what was experienced on SOHO as described above. However, one must protect against weaknesses in the overall conservative nature of the pre-launch analysis. For example, the analysis may not properly account for observatory structural modes being excited, particularly by high-frequency harmonic content (tones) of the various disturbance sources. All of this points towards the need for rigorous pre-launch DIT campaign.

2.5. James Webb Space Telescope (JWST)

On the JWST science observatory the ACS provides attitude determination and control for all mission phases and modes of the observatory. JWST uses six RWs to generate control torques to orient the observatory with ACS sensing functions performed by three star trackers and six gyroscopes. This enables coarse pointing sufficient to keep the SA pointed at the Sun and the high-gain antenna pointed at the Earth. To take images and spectra of astronomical targets, finer pointing is needed. The ACS therefore interfaces with the Fine Guidance Sensor (FGS), located in the Integrated Science Instrument Module (ISIM), and with the telescope's fine steering mirror (FSM) for fine pointing control during observations. JWST's requirement for telescope Line of sight motion is <3.7 mas. As described in [25], a two-stage passive vibration isolation system will be used on JWST to attenuate higher frequency (>2.0 Hz) micro-vibration disturbances associated with RW static and dynamic imbalances, as well as bearing run-out [25]. The JWST Stage 1 isolation consists of 7.0 Hz RW isolators located between each RW and the spacecraft bus, while the Stage 2 device is a 1.0 Hz tower isolator between the spacecraft bus and the observatory's Optical Telescope

Element (OTE). The RWs are speed biased to 2700 rpm by using an additional bias control loop that regulates RW speed operation near a fixed speed in the null-space of the RW cluster. This RW speed bias set point is needed to maintain RW speeds within an acceptable speed range of 15Hz to 75Hz in order to avoid exciting structural vibrations that may contribute to LOS jitter.

2.6. Geostationary Operational Environmental Satellite (GOES)

GOES-16, previously known as GOES-R, is the first of the next generation GOES-R series of GOES operated by the U.S. National Oceanic and Atmospheric Administration (NOAA). The GOES-R series program is a collaborative effort between NOAA and NASA. These advanced meteorological spacecraft were designed and built by Lockheed Martin and their acquisition technically and programmatically managed by NASA GSFC in Greenbelt, Maryland. GOES-16 was launched on 19 November 2016 and, as described in [26] it represents a dramatic performance leap in Earth and solar weather observation capabilities. However with the improved metrological payload resolution comes the instrument suite's increased sensitivity to micro-vibration disturbances over the broad frequency range of 0-512 Hz. Disturbance sources include RWs, thruster firings for station keeping and momentum management, gimbal motion, and internal instrument disturbances. To minimize the impact of these disturbances, the baseline GOES-R design includes an Earth Pointed Platform (EPP), which is a stiff optical bench on which the two nadir pointed instruments are collocated together alongside the GN&C subsystem's star trackers and Inertial Measurement Units (IMUs). The EPP is passively isolated from the spacecraft bus with Honeywell D-Strut isolators [27] providing attenuation for frequencies above approximately 5 Hz in all six Degrees-of-Freedom (DOF). A switch in RW vendors occurred late in the development of GOES-R program. To reduce the risk of RW disturbances impacting performance, a secondary passive isolation system manufactured by Moog CSA Engineering was incorporated under each of the six 160 Newton-meter-second (Nms) RWs. This secondary passive isolation system was specifically tuned to provide attenuation at frequencies above approximately 50 Hz. Integrated wheel and isolator testing was performed on a Kistler table at NASA GSFC. High-fidelity simulations were conducted to evaluate jitter performance for four topologies: 1) hard mounted no isolation, 2) EPP isolation only, 2) RW isolation only, and 4) dual isolation. The pre-launch simulation results, as reported in [28], demonstrated excellent performance relative to the GOES-R pointing stability requirements, with dual isolated LOS jitter predictions being less than 1 micro-radian. A comparison of pre-launch to post-launch GOES-16 satellite dynamic interaction characterization results is documented in [29]. In particular, the GOES-16 post-launch on-orbit dual isolation performance characterization test results, as described in detail in [29], indicate in-flight dynamic behaviors in general agreement with pre-launch analytical predictions.

2.7. Wide Field Infrared Survey Telescope (WFIRST)

Scheduled to launch in the mid-2020s, the proposed Wide Field Infrared Survey Telescope (WFIRST) would~~will~~ have 300 megapixel Wide Field Instrument that ~~will~~ images a sky area 100 times larger than HST. Given the demanding micro-vibration challenges and multi-disciplinary nature of the problem there is extensive use of Integrated Modeling (IM) and integrated performance analysis on WFIRST as was done on JWST [30].

In addition to its Wide Field Instrument, the baseline design of WFIRST ~~will~~ also features a coronagraph technology demonstration instrument designed to directly image exoplanets by blocking out a star's light, allowing the much fainter planets to be observed. As NASA's first advanced coronagraph in space, it ~~will~~ would be 1,000 times more capable than any previously flown. Internally the WFIRST CoronaGraph Instrument (WFIRST-CGI) includes both a Shaped Pupil Coronagraph (SPC) and a Hybrid Lyot Coronagraph (HLC). This WFIRST-CGI requires unprecedented levels of stability over multiple hours (5 to 100) of observations, while requiring these levels of stability to be repeatable in a Root Mean Squared (RMS) sense from observation to observation. The level of pointing stability required is 0.7 mas RMS per axis per observation and has to be repeatable at the 0.5 mas RMS level from observation to observation. In addition to stability, the pointing system bias must also be repeatable at the 0.1-mas level between observations. These pointing requirements are paramount to maintaining the needed raw contrast levels between the intensity level of the star of interest and the level of obscuration achieved by the two internal coronagraphs. To meet these requirements, the WFIRST-CGI team takes advantage of the spacecraft's ACS (a 8-mas 1-sigma/axis class pointing system) and passive jitter designs (12-mas 1-sigma/axis class passive jitter design driven by the dual isolated RWs) already planned for WFIRST while constraining the RW speeds to regimes favorable to the control system bandwidth in CGI (30 Hz). While the CGI design is currently meeting its requirements, this could easily change between SRR (the current project phase) and Launch, as the IM team matures its design and models. So, to allow maximum design freedom to the IM team, the exported jitter requirement flowed down to them contains the CGI team's closed loop rejection function to allow quick assessment of exported jitter to CGI after the CGI control system is used.

2.8. Space Interferometry Mission (SIM)

The Space Interferometry Mission (SIM) science goals were to provide direct measurements of the wobble of stars due to orbiting planets, while doing wide and narrow angle astrometry, and generating a star-catalog that will be orders of magnitude better than the Hipparcos catalog. The proposed SIM payload included three stellar interferometers, each with a baseline of 10 meters, and an interferometric baseline vector defined by each of the interferometers' pair of primary mirrors. Of the three interferometers, only one was used for science data collection, while the other two were used to accurately measure the changes in attitude of the science interferometer's baseline attitude in space. SIM used a network of metrology beams (external metrology) to transfer the attitude measurements made with the guide interferometers to the science interferometer's baseline attitude. The SIM project made considerable investments in the development of interferometer metrology technology (see [31]). The requirement on relative attitude knowledge obtained by each interferometer over all time scales up to 1 hour was 0.2 mas RMS. To meet this requirement SIM had to form and track starlight fringe position for each of its interferometers to less than 10 nanometers RMS for observations as long as 1 hour. This level of performance was accomplished using a multi-disciplinary approach that combined the ACS, the structure, the instrument stability, and the instrument's own fringe tracking system, which included a complex network of metrology systems. Key aspects of the design were:

- A 2-arcsec class spacecraft ACS for rigid body motion pointing control,
- A precision support structure that minimized thermal distortion and response to jitter sources,
- A dual stage isolation system for the 6 RWs on the spacecraft,
- Precision optical mounts and mechanisms that minimize their susceptibility to disturbance while also minimizing their generation of jitter,
- External metrology to relate attitude from the guide baselines to the unmeasured attitude of the science baseline,
- Internal metrology to measure the changes in optical path traveled by the starlight on both arms of each interferometer
- A fast steering mirror to compensate for each telescope's aperture pointing error to the tune of 30 mas RMS (two per interferometer), and
- A three-stage active mechanism for each interferometer to compensate for all residual fringe tracking errors.

Given the unprecedented level of stability required, it was clear from the beginning that modeling uncertainty was going to be an issue for SIM. How much uncertainty is there in model based predictions? Is the uncertainty in modeling under predicting or over-predicting performance? If predictions are scaled by some agreed upon level of uncertainty in models, and requirements are broken, should the project spend budget and resources to attack design deficiencies? At what point in the design cycle should the project react to these results?

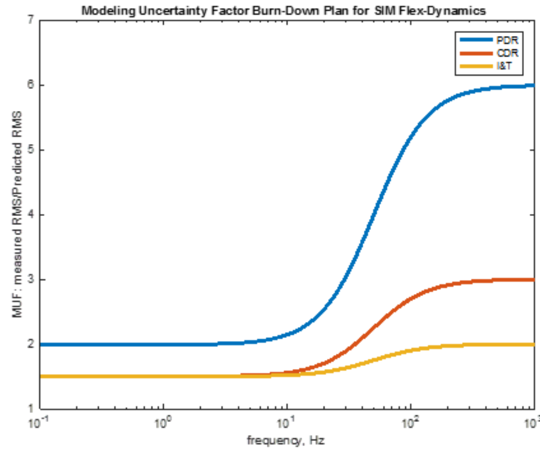


Figure 1. SIM Flight System Modeling Uncertainty Factors for Flexible Dynamics

The SIM project built a full-scale testbed version of the flight system, called the STB3, which included the instrument, spacecraft, dual isolation system, and a pseudo star for a "test as you fly" style technology demonstration and modeling verification [32-34]. The idea was to demonstrate directly the feasibility of achieving the stability and knowledge requirements discussed above. An additional benefit of building STB3, was that we could compute the prediction error of our models vs. actual measurements of instrument performance out to 1 KHz, which would give us a realistic notion of uncertainty. These comparisons were made for three levels of model fidelity consistent with common modeling practices at Preliminary Design Review (PDR), CDR and post Integration & Test (i.e., after model correlation is concluded).

Figure 1 shows the uncertainty functions based on the ratio of measured performance to model predictions in STB3. Some level of smoothing was used to allow easy adoption by the flight system. In all cases, models under-predicted testing, and the predictions got better as model fidelity increased. While this was expected, the real value of this work was to provide a sense of scale for the uncertainty. Along with these functions goes the assumption that flexible body dynamics damping is equal to 0.25% for all modes in the models, and that the first flexible body frequency is above 10 Hz (excluding the isolation system, which had modes between 2 and 7 Hz). A key point to note is that even after test-to-model correlation work was done, the predictions continued to under-predict the measurement. The functions in Figure 1 were adopted by the Jet Propulsion Laboratory (JPL) Dynamics and Controls team to appropriately scale their raw predictions and to recommend SIM design changes as needed, so that at PDR, CDR and post testing during the integration and test phase the flight system could always show positive margins against requirements

2.9. Soil Moisture Passive Active (SMAP)

The Soil Moisture Passive Active (SMAP) synthetic aperture radar pointing system was driven by the need to reconstruct its boresight pointing angle and the need to calibrate the boresight of the Stellar Reference Unit to the boresight of the reflector boresight as it spun at 0.25 Hz. The micro-vibrations problem was from the start a non-issue for SMAP given its large boom (6 meters) and large reflector (6 meters in diameter) which acted as isolators with corner frequency at 1.75 Hz while the RWs were biased to operate between 34 and 40 Hz. The wobble of the boom/reflector pair due to mass imbalance (dynamic and static) never interacted with the flexible body dynamics of the instrument or with the SAs (the first SA flexible mode was greater than 3 Hz). The speed control error in the spun instrument assembly never generated disturbances large enough to excite the flex dynamics of the boom/reflector noise to appreciable levels in analysis or in flight. A small but significant surprise in SMAP was the measured damping. The design assumed 0.25% damping to be very conservative, but a direct measurement using the on-board gyro sampled at 200 Hz yielded an in-flight value of only 0.15% for the reflector first mode, which was previously outside of the JPL experience base. Note that the reflector mode with this level of damping was primarily straining the small prime-batten metal boom connecting the reflector to the rest of the large 6-meter boom, no room for anything other than pure material damping should be expected in this case.

2.10. NASA-ISRO Synthetic Aperture Radar (NISAR)

Using advanced radar imaging that will provide an unprecedented, detailed view of Earth, the NASA-ISRO Synthetic Aperture Radar, or NISAR, spacecraft is designed to observe and take measurements of some of the planet's most complex processes, including ecosystem disturbances, ice-sheet collapse, and natural hazards such as earthquakes, tsunamis, volcanoes and landslides.

The driving requirement on NISAR is repeatability of boresight pointing. It requires the system to repeat its pointing angle at each point on Earth seen by the instrument every 12 days to better than 53.4 milli-degrees 1-sigma per axis. The main sensitivity for NISAR is not micro-vibrations but thermal distortion. The thermal distortion stability of the system is driven by the variations of solar beta angle over its orbit, especially at the poles. Micro-vibrations are not an issue in part because the reflector and boom pair (12-meter diameter and 9-meter long respectively) have very low modal frequencies (the first mode is at 0.5 Hz) when compared to the disturbances generated by the RWs. Since the first mode is at 0.5 Hz the RWs are speed biased above 16 Hz. Also, the boom and reflector act as very effective isolators against any disturbances generated by the RWs, the SA motion, or the HGA slewing.

2.11. BepiColumbo

The BepiColombo spacecraft, which is scheduled to launch in October 2018, is an ESA mission to Mercury, in collaboration with the Japan Aerospace Exploration Agency (JAXA). BepiColombo is the 5th cornerstone in ESA's Cosmic Vision Scientific Program. As described in [33], the performance of the on-board instruments during scientific observation periods may be impaired by the effects of micro-vibrations due to the RWs and the SA and the HGA drive mechanisms. Since most of the instruments require continuous and highly accurate nadir-pointing, stringent requirements are imposed on the spacecraft pointing stability. In particular, the line-of-sight stability must be better than 1 arcsec over 1 second and better than 0.1 arcsec over 1 msec. The requirement on rotation around the LOS is more relaxed (20 arcsec over 1 second and 2 arcsec over 1 msec). These pointing stability performance targets are required to be met 95% of the time over the 2 years of science operation around Mercury.

An analytical micro-vibration study was performed by the prime contractor to confirm that the above instrument stability pointing requirements are satisfied 95% of the time in the face of the RW disturbances, the HGA (which continuously tracks Earth during science observation periods) disturbances and the SA disturbances. The 95% probabilistic stability requirement presented a unique verification challenge for the BepiColumbo jitter team. A Monte Carlo based simulation approach was ruled out as it would have required different spacecraft FEMs for each HGA and SA orientation considered. The pointing stability requirements were interpreted as temporal, meaning that the requirements shall be met 95% of the 2-year mission time while considering the entire population of observatory configurations as well as wheel speeds and HGA/SA drive mechanism speeds. Unfortunately, it was not possible to identify, in an a priori manner, a worst-case scenario, meaning the worst-case combination of HGA and SA orientations together with worst-case mechanisms/wheel speeds. Therefore, the approach adopted was to compute confidence intervals for the complete population based on the data extracted from seven specific cases analyzed. As a side note, it was interesting to note that, according to [33], the Kistler table wheel disturbance characterization testing was performed using an "old" RW that was expected to be operationally representative of the actual BepiColombo flight wheels. However, the Kistler test data on this particular RW revealed anomalously high axial and radial disturbance forces. An investigation indicated that the "old" RW used for the characterization testing may have had a damaged bearing and thus produced disturbance levels not truly representative of the flight wheels. The Kistler testing was repeated with an Engineering Qualification Model of the BepiColombo wheel to obtain a more accurate set of disturbance data with which to validate the analytical RW models. This particular experience points to the critical need to ensure that the disturbance characterization testing is performed using component test articles (e.g., RWs) that faithfully represent the dynamical behaviors of the flight hardware. To do otherwise could lead to wasted test and analysis time/energy attempting to reconcile anomalous disturbance data. In some cases, to obtain the most faithful representation, the actual flight hardware may need to be tested which imposes some project risk.

2.12. Meteosat Third Generation (MTG)

The Meteosat Third Generation (MTG) program, which is being performed in a cooperation between Eumetsat and ESA, has as its goal the renewal of the current Meteosat Second Generation set of spacecraft to ensure continuity of space-acquired high-resolution meteorological data to beyond at least the early 2040s. The MTG program will see the launch of a constellation of six new geostationary (imaging and sounding) satellites from 2021 onwards. Unlike the previous generations, the MTG constellation will consist of two types of satellites based on the same platform. The MTG satellite series will comprise four imaging (MTG-I) and two sounding (MTG-S) satellites. The future MTG generation will rely on three-axis stabilization for both the MTG-I and the MTG-S spacecraft, which is a significant change from the Meteosat Second Generation spacecraft dual-spin stabilization approach. Three-axis platform stabilization was dictated by the MTG mission's need for instrument imaging dwell times that were incompatible with the spin-stabilization approach. Three-axis platform stabilization by its nature requires a more complex set of attitude control actuators (e.g., RWs) which constitute an instrument pointing disturbance source not present on the previous dual-spin stabilized Meteosat Second Generation spacecraft. In a similar manner the MTG's instruments increased radiometric resolutions drive the need for very low instrument detector temperatures, temperatures which cannot be achieved with passive cooling techniques. Thus the introduction of an active cooling mechanism on-board the MTG spacecraft adds another new disturbance source to its instrument LOS pointing. The MTG-I imaging instrument, called Flexible Combined Imager (FCI), features performance requirements similar to those of the Advanced Baseline Imager (ABI) of GOES-16 (GOES-R). As described in [36] the FCI's sharpest resolution of 500 meters calls for a micro-radian level stability over the 0.5 msec pixel integration time. The Infra-Red Sounding (IRS) instrument that will fly on MTG-S is also susceptible to micro-vibrations but in a different frequency range due to its much longer dwell time of 10 seconds. In both cases, ACS actuators, SA drive mechanisms, and instrument active coolers required to reach the demanding infrared radiometric requirements, are potential sources of line of sight jitter. Reference [36] also presents the MTG micro-vibration requirements derived from the mission specification, and addresses potential solutions to the MTG micro-vibration problem. The engineers working on MTG have developed a number of simulations and tests in their attempt to "master the effect of micro-vibrations on the instruments image quality". As explained in [33] the MTG engineers, by conducting early simulations and tests, were able to identify passive disturbance isolation solutions to keep the impact of micro-vibrations on the LOS jitter within the defined requirement and with sufficient margins.

3. GENERAL APPROACH TO ADDRESS THE MICRO-VIBRATION PROBLEM

As alluded to above the micro-vibration challenge consists of protecting against degraded output performance of the payload's optical sensors caused by the transmission of spacecraft internal mechanical disturbances from their source through the vehicle's structure to the sensing elements in the payload instruments. These optical degradations typically occur due to high-frequency (relative to the spacecraft's attitude control bandwidth), low-energy excitations of the spacecraft system's structural modes of vibration that often possess very low inherent damping. For the majority of NASA's science missions the micro-vibration problem solution is focused on the modeling, analysis, and test of precision optical-mechanical space observatory systems (i.e., a spacecraft bus supporting a science instrument payload) but micro-vibration can also impact precision pointing of steerable HGAs. Depending on the nature of the "transfer function" of a given space vehicle configuration (i.e., the structural input/output model between a disturbance input node and the payload sensor output node of interest) the spacecraft structure will either amplify or attenuate that particular disturbance. The structure's resonant frequencies, the damping level in the system and significant system non-linearlites are the key parameters influencing this amplification/attenuation dynamic behavior. The level of structural mode damping assumed in the system model will have a great influence on the level of micro-vibration seen at the structural resonance frequencies. In spacecraft micro-vibration analyses it is not uncommon to use values in the range of 0.5% to 0.25% damping (uniformly applied to all vibration modes) resulting in dramatically high resonance amplification factors (i.e., Q) in the 100-200 range at the resonant modes of the spacecraft structure. The SDO experience revealed that a damping ratio of 0.3% was a good value for jitter analysis for a conventional structural system at a typical (non-cryogenic) temperature range [23]. In certain relatively rare micro-vibration studies the damping values used could potentially be in the lower range of 0.1% to 0.25%. Recall that on SMAP, as mentioned above, JPL engineers directly measured an in-flight damping of only 0.15% for the reflector first mode.

4. UNIFORM ENGINEERING PRACTICES FOR APPROACHING AND SOLVING THE MICRO-VIBRATION PROBLEM

In the view of the authors, there is a general lack within the spacecraft engineering community of well-established and published engineering guidelines defining uniform practices for the process of assessing, controlling and managing observatory micro-vibrations. For example at NASA there currently is no existing Agency-level set of established best practices for performing observatory jitter analysis. This is not to say that several of the spacecraft engineering originations at the NASA Centers do not have their own in-house best practices for performing observatory-level jitter analysis. The degree to which these are documented and shared across the Agency is very limited however.

Documenting these best practices for performing observatory-level modeling, simulation, analysis, and test activities associated with solving the spacecraft micro-vibration problem is a goal of the NASA Engineering and Safety Center (NESC) GN&C Technical Discipline Team (TDT). The NESC GN&C TDT is chartered to perform such GN&C discipline knowledge capture work in support of NASA's goals for retaining and sharing Agency-wide, highly-specialized engineering 'tribal knowledge'. In addition, the NESC GN&C TDT is interested in capturing relevant lessons learned from past missions that have dealt with the spacecraft micro-vibration problem, successfully or otherwise. Later on in this paper, some specific and relevant micro-vibration lessons learned will be presented.

Before leaving this discussion of micro-vibration engineering knowledge capture, the authors would like to single out one very significant contribution, in their view, to the community's common knowledge base for approaching and solving the spacecraft micro-vibration problem. Readers are encouraged to refer to Section 13.3, entitled "Micro-vibration", of the Spacecraft Mechanical Loads Analysis document (ECSS-E-HB-32-26) that has been prepared and publically released by the European Space Agency/European Cooperation for Space Standardization (ESA/ECSS) organization [1]. This document provides an excellent resource for engineers covering the general aspects of the spacecraft micro-vibration problem, and also presents some detailed information on micro-vibration analysis, modeling requirements, LOS budgeting assessment and pointing error synthesis, and a discussion on micro-vibration verification testing.

In the remainder of this section of the paper the authors will attempt to provide their high-level view of the activities a multi-disciplinary engineering team might consider pursuing to address and solve the spacecraft micro-vibration problem.

5. ACTIVITY FLOW FOR APPROACHING AND SOLVING THE MICRO-VIBRATION PROBLEM

A technically sound spacecraft micro-vibration effort consists of both analytical work and focused testing. As described above fundamentally micro-vibrations can cause undesired distortions on the payload instrument's sensitive optical axis LOS pointing. Although individual programs/projects may have mission-unique definitions of "LOS jitter" one can in general consider this to be undesired motion of a payload's sensor optical boresight axis over the duration of the sensor's focal plane integration time. The sensor's focal plane integration time(s) is a key parameter in any assessment of LOS jitter in that it determines the frequency range(s) of critical interest for mitigating the unwanted effects of micro-vibration.

A most important message the authors wish to convey to the reader is the imperative of focusing on and making critical architectural decisions early on in the process. Architectural decisions made early in a project's lifecycle always have long-term mission consequences and ramifications. It is not an overstatement to point out that, more often than not, mission success will depend on the quality of the observatory-level architectural decisions that are made in the early stages (e.g., the Formulation Phase) of a project lifecycle. In order to make the 'best' (i.e., the most-informed) architectural decisions both a comprehensive process and an associated multi-disciplinary jitter team organization needs to be established early on.

While as previously mentioned this is truly a "Systems" problem the necessary detailed technical subject matter expertise to properly solve the spacecraft micro-vibration problem is often not readily available from within the System Engineering team. The System Engineering team is usually most skilled at requirements definition and flowdown (e.g., pointing and jitter error budgeting) as well as performing observatory-level technical management, and ensuring that sufficient cross-discipline communications and coordination occurs.

The Jitter Team therefore needs to be thoughtfully and carefully composed of the necessary engineering discipline specialists from GN&C, Structures, Dynamics, Mechanical Systems, etc. This team then needs to take "ownership" of the problem early in the process. That team's first order of business is identify and then directly deal 'head on' with the fundamental micro-vibration challenges for their particular mission application.

Typically designing and developing the appropriate level of micro-vibration control to suppress and/or isolate the effects of on-board disturbances requires extensive analysis, modeling, simulation, as well as comprehensive ground-based testing at both the component and subsystem levels (e.g., disturbance source characterization testing) and at the integrated system level to assess end-to-end performance. In many cases, post-launch in-flight testing is also performed to validate pre-launch modeling adequacy and to update system performance predictions based upon the analysis of data collected in the actual mission operating environment.

Before starting the design process, a jitter analyst should recognize and understand that not all observatory designs require the same level of care and attention when it comes to solving the micro-vibration problem. The design process is of course iterative, but one must start a new design somewhere. The following are some recommended rules of thumb, based on the author's experience, for a representative set of observatory stability requirement cases (expressed in RMS per axis, 1-sigma values), which are intended to provide some guidance on where to initiate and how to approach a new micro-vibration design:

Case 1. **Stability > 100 arcsec**

- Not a micro-vibrations challenge for any length of instrument FPA integration time (short or long)
- Testing needed for workmanship. Performance testing not really needed at system level. Should be able to show good margins
- Only needs some structural, and rigid body tailoring and good architectural choices for ACS.

Case 2. **10 arcsec < Stability < 100 arcsec**

- Starts to be a micro-vibrations problem in the NISAR/SMAP class. Is not difficult but some modeling will be needed.
- Testing for workmanship and model validation. Performance testing still an option at the system level, but good idea at the subsystem/component level if possible. Should have good margins against worst possible scenarios
- Requires a solid ACS, well balanced wheels, some structural tailoring. Pay attention to rigid body dynamics, knowledge.

Case 3. **0.1 arcsec < Stability < 10 arcsec**

- A difficult problem, Chandra class. Science success or mission success are now a direct or nearly direct, function of pointing stability or Wave Front Error (WFE) stability
- Testing for workmanship, model validation, performance as high up the system chain as possible. Modeling now has to be used to make design changes in order to keep positive margins against requirements throughout design phase. Modeling fidelity needs to be higher at all stages of design
- Recommend introduction of Modeling Uncertainty Factors (MUFs) when predicting performance. MUFs have to be chosen carefully so as to not drive the design unnecessarily. MUFs should have phased "reduction" plan based on clear milestones in the project's design, modeling, and testing phases. One approach might be to establish MUFs as a function of both specific frequency regimes and the state of observatory design maturity.
- Requires very good ACS with high-performance gyros and star/celestial sensors as well as very well balanced RWs. May be necessary to "cherry pick" flight RWs and may have to have operational constraints for wheel speeds, and/or a single layer of isolation for wheels), good structural tailoring. May also have to isolate cryopumps and cryocoolers.

Case 4. **0.01 arcsec < Stability < 0.1 arcsec**

- Very difficult and risky problem in the SIM and Space Infrared Telescope Facility (SIRTF) class. Not easy to achieve, need very careful management at system level. Science requirements and/or mission success now depend on pointing and/or WFE performance.
- Testing for workmanship, model validation, performance as high up the system chain as possible. Modeling now has to be used to make design changes in order to keep positive margins against requirements throughout design phase. Modeling fidelity needs to be higher at all stages of design. System level testing will be required in some way (e.g., a broad band modal test for structural model correlation).
- Requires very good ACS, (with high-performance gyros and star/celestial sensors and finely balanced RWs) as well as FGS for ACS during fine pointing mode operations. May be necessary to pay for super fine balancing of the RWs, and even then may have to carefully "cherry pick" the flight RWs. A very well-tailored RW dual stage isolation system may need to be considered.

Case 5. **0.001 arcsec < Stability < 0.01 arcsec**

- Very difficult/risky problem in the WFIRST-CGI. Very difficult to achieve, need very careful management at system level. Science requirements and/or mission success now depend directly on pointing and/or WFE performance.

- Testing for workmanship, model validation, performance as high up the system chain as possible. Modeling now has to be used to make design changes in order to keep positive margins against requirements throughout design phase. Modeling fidelity needs to be higher at all stages of design. System level testing required with distributed sensing in common path with "light path" (broad band modal testing for structural model correlation)

- Requires all of the above, plus choice of distributed sensing for jitter and drift and instrument compensation system with 10 to 200 Hz bandwidth. Will require very high-performance ACS Fine Guidance Sensor in each instrument. Will require best RWs possible while still cherry picking. Super-fine balancing of wheels is a must. If RWs are used then this will need low frequency dual isolation, while paying attention to any change in dynamics. Could potentially replace RW's with cold gas micro-thrusters. Observatory will most likely have to operate in a benign environment such as Sun-Earth System L2 point instead of earth orbiting. Will have low agility, hence mostly inertially fixed during science observation periods. Observatory design should make it a priority to minimize the Center-of-Pressure to Center-of-Mass migration in order to be able to bias wheels when they are used, or minimize thrusting when using micro thrusting. Need to pay attention to beam-walk within optics, but can still compensate in the back end with instrument control system.

Case 6. **0.0001 arcsec < Stability < 0.001 arcsec**

- Extremely difficult and challenging engineering problem in the class of the Habitable Exoplanet Imaging Mission (HabEx) and/or the Large UV/Optical/IR Surveyor (LUVOIR) mission concepts. Multiple micro-vibration engineering and technology risk areas to be mitigated. Must contend with distributed constraints on beam walk (assuming a telescope).

- Will clearly need high-performance ACS with micro-thrusters to avoid RW disturbances while adapting a Fine Guidance Sensor and dropping the isolation (HabEx baseline design).

- Design risk is reduced greatly because stability requirements in this class preclude the use of conventional RW's, so their disturbance is no longer an issue. Modeling pressure also reduced, but all of the above still needed. Levitating RWs may be an option in the future as for Luvoir mission.

As it was mentioned several times in the above 'rules of thumb' a good starting point for the discussion of the typical observatory jitter analysis process is the design of the spacecraft's ACS. This is true even though we know that micro-vibrations in the high-frequency regime do not typically drive the ACS design since the frequency spectrum of the micro-vibrations is so far beyond that of the typical ACS bandwidth. Simply put the function of the ACS is to control the observatory's rigid-body motions while simultaneously stabilizing the low-frequency flexible-body appendage vibration modes occurring within or near the ACS bandwidth. Figure 2 portrays the typical high-level ACS analysis and design process. One key aspect of the ACS design process to keep in mind is that a Reduced Order Model (ROM) of the observatory's flexible body dynamics is employed in which only relatively low frequency modes are incorporated. Specifically these would be the flexible body appendage modes occurring within or near the bandwidth of the ACS attitude controllers. Commonly the ACS controller bandwidths are in the low-frequency range of 0.01 Hz to 0.1 Hz. In special cases where very tight attitude control requirements exist, the ACS bandwidths could possibly approach 1 Hz but it is unlikely that they would be much higher than that. As illustrated in Figure 2 these flexible body modes of particular interest to the ACS designers would emerge from a modal significance analysis (typically a process that identifies flexible modes with the highest levels of mass participation) and would generally be at frequencies less than 5-10 Hz. This subset of modally significant flexible body modes would then be used in the mandatory analyses of the stability of each and every ACS sensor-to-ACS actuator loop. For some mission classes the initial ACS-level stability and performance analyses are often done independent of the observatory-level jitter assessment. However there is no doubt that the ACS designers would certainly be called upon to support the jitter assessment process as the observatory design matures. As will be shown the resulting ACS model will be a critical element of the system-level observatory jitter analysis process.

Figure 3 provides an illustrative flow chart of the modeling, simulation, and analysis (and some test) activities typically involved in the overall observatory jitter analysis process. Clearly, the flow of activities shown in this flow chart can be tailored depending on specific mission-unique requirements and design priorities, as well as the available project resources.

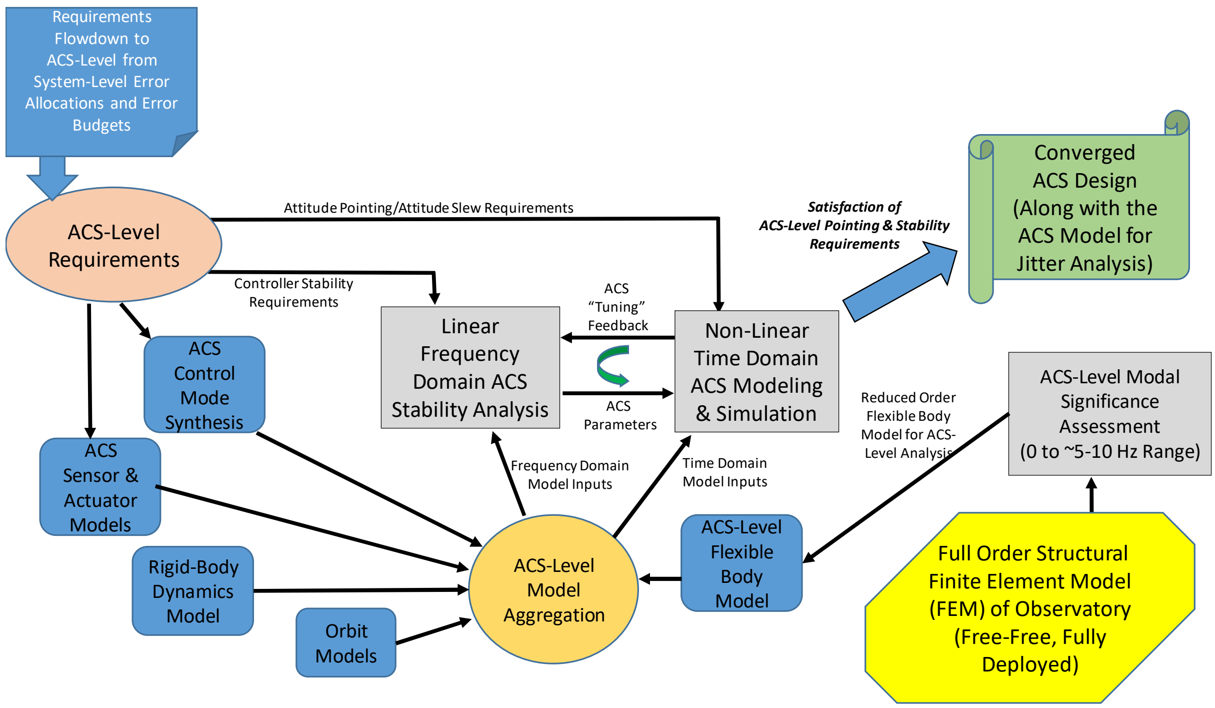


Figure 2. Typical High-Level ACS Analysis and Design Process

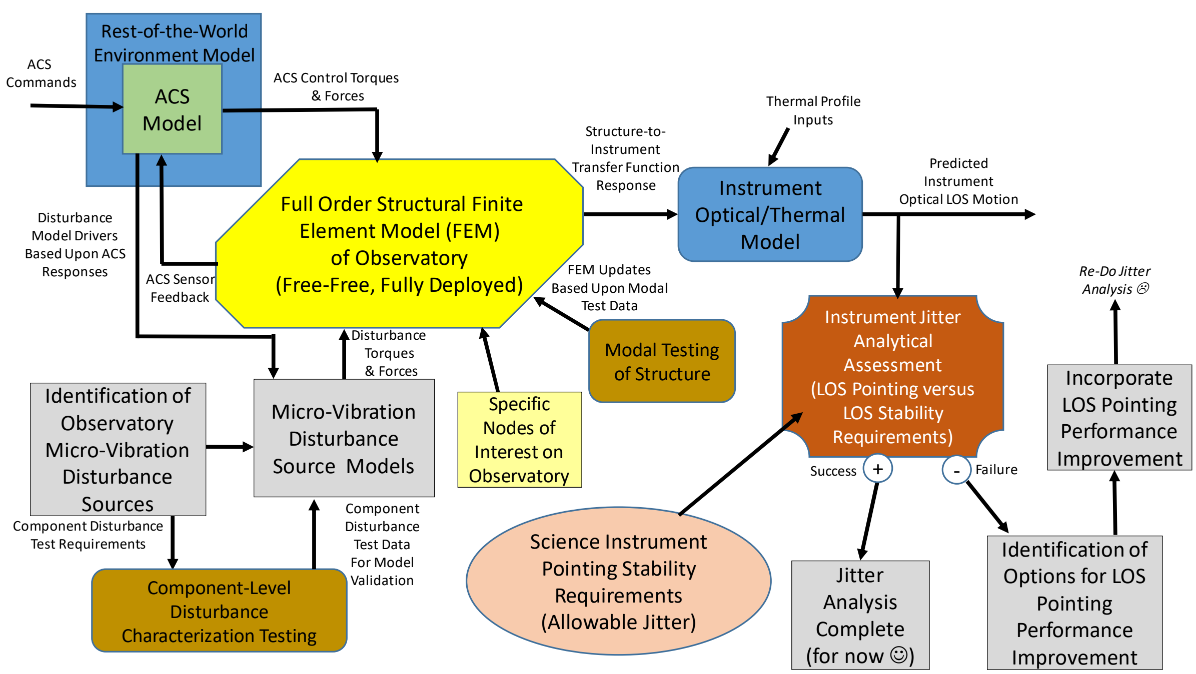


Figure 3. Typical High-Level Observatory Micro-Vibration (Jitter) Analysis Process

6. DISTURBANCE MODELING

It is generally true that each observatory has its own unique micro-vibrations disturbance environment that will need to be examined and characterized. As mentioned above micro-vibration inducing disturbances can arise from bus-mounted rotating mechanical devices such as RWs and/or MWs and also such devices as cryocoolers and cryopumps. Other micro-vibration sources could include internal payload mechanisms and appendage drive mechanisms. Attitude control/station-keeping/momentum dumping thrusters may also need to be considered as sources of micro-vibration disturbances.

For a given observatory, the jitter team will need to conduct an initial assessment of their mission-unique set of micro-vibration disturbances sources and then decide on a comprehensive plan for their particular disturbance modeling campaign. This plan should include the associated component-level testing to inform and validate disturbance models.

During the manufacturing process, the RWs are almost always balanced by the vendor to minimize the vibrations that occur during in-flight operation due to static and dynamic imbalances. However, it has been found that the vibration forces and torques emitted by even a normally 'well balanced' RW can still degrade the performance of precision instruments on observatories. A rotating RW can generate a variety of sub-harmonics and higher order harmonics, even if well balanced, resulting from bearing interactions. These disturbances generated by RWs are of variable frequency unlike the disturbance frequencies generated by CMGs and cyrocoolers, which are devices that tend to operate for long periods of time at the same fixed speed of motion. Over its range of rotating speeds a RW will produce a fundamental disturbance tone and number of harmonic tones. Disturbance tones which quite likely can excite (i.e., couple with and amplify) flexible structural modes causing micro-vibrations at critical payload instrument locations. Therefore, managing and controlling the disturbances of the constantly running variable-speed RWs tends to be more challenging. Thus, it is not surprising that on the whole RWs have been the principal sources of spacecraft on-board disturbances on NASA missions. A close second are the cryocoolers, followed by the SA drive mechanisms and the HGA drive mechanisms. Of course, these are very general observations and each observatory will have its unique sources of LOS pointing disturbances. In some cases the payload-induced disturbances that are the most troublesome. This payload dynamic interaction can sometimes occur within a single instrument and other times it occurs among payload instruments. Some form of payload instrument self-compatibility testing may be required to assess the degree of the dynamic interaction.

Given the predominance of RW-induced disturbances it is not too surprising that the literature is well populated with detailed technical information on the nature of RW disturbance characterization and modeling (see for example [37–49]). It is not within the scope of this paper to delve into the details of RW disturbance modeling so we will constrain ourselves to some high level remarks on this topic.

As described in both [40] and [45] the primary root-sources of disturbances in rotating mechanisms such as RWs are: 1) mass imbalances, both static imbalance and dynamic imbalance, 2) ball bearing imperfections, in the inner and outer races as well as the balls themselves and even the bearing cage, and 3) motor properties such as the commutation noise, resulting from the electronic switching, in a brushless DC motor, between stator phases upon passage of the magnetic poles of the rotor. There may also be RW structural resonances to contend with as well which contribute to the micro-vibration disturbance environment.

As generally described in the cited RW disturbance references it is fortunate for jitter analysts that these root-sources of disturbances in rotating mechanisms such as RWs tend to adhere to established and, more or less, well-understood rules of physics. It is also fortunate that there are a number of ground-based micro-vibration test facilities [50-55]. These high-end precision-test facilities have established techniques for isolating, measuring, and generating micro-vibrations in a well-controlled test environment. For example, [55] describes the test capabilities of a 6-DOF micro-vibration isolation, measurement and generation facility recently developed by the British National Physical Laboratory for ESA's test center in Noordwijk, the Netherlands. Precision testing to experimentally collect RW disturbance data to inform modeling activities can serve to mitigate mission risk. These test facilities can also collect similar data generated by other spacecraft components such as cryocoolers.

Lastly, on a historic note, in the course of searching the literature the authors identified a report (see [56]) documenting one of the very first activities to measure RW emitted vibrations (both forces and torques) about three orthogonal axes during constant wheel speed operation, as well as during acceleration and deceleration. This work was performed by Sperry Flight Systems in 1975 for NASA's Marshall Space Center (MSFC) in order to provide the measured RW disturbance data to prime contractors for LST Phase B studies. Of course this so-called LST was to later become far better known as the HST.

7. STRUCTURAL FINITE ELEMENT MODELING

Obviously, any jitter analysis is reliant on obtaining an accurate FEM representation of the entire observatory's structural dynamics. Observatory flexible body modes of vibration are of interest to jitter analysts over a widely extended frequency range, reaching frequencies up to and beyond the 100-300 Hz range, in some special cases perhaps as high as 1000 Hz. This is because in some cases an observatory's disturbance environment may contain high-frequency wheel-induced vibration spectral "tones" possessing sufficient energy to excite structural vibration modes at frequencies as high as 300 Hz large enough to negatively impact jitter performance. The FEM challenge then is to accurately represent the dynamics of large lightweight flexible observatory structures that may have hundreds, if not thousands, of closely spaced light-damped modes of vibration. One experience-based rule of thumb states that modeling of structural modes becomes increasingly inaccurate above approximately the 50th system normal mode.

A structural FEM of the fully deployed "free-free" observatory is typically developed for multiple physical states. At a minimum, there is a FEM for both the Beginning of Life (BOL) and End of Life (EOL) spacecraft configurations. Quite possibly additional FEMs are created reflecting various orientations, relative to the core spacecraft body, of the SAs and/or other flexible appendages and perhaps for different states of the propellant mass.

Fundamentally, these FEMs will permit analysts to investigate the transmission path through the Observatory structure from the location of an individual disturbance source (e.g., a RW disturbance force input node) to a specific location of interest within the science payload (e.g., a model output node at the focal plane array of a particular instrument). Figure 4 displays, in the frequency domain, a representative example of an Observatory structural transfer function response between a disturbance component and an instrument rotational LOS DOF.

The FEM typically provided to the jitter analyst is a very high order system matrix which is not particularly easy to manipulate, and from which it is difficult to directly gain informative physical insights. Typically, jitter analysts have a toolset that will create a more simplified lower-order state-space model from the modal frequencies and normal modes reported by the structural FEM (i.e., using the computed eigenvalues and eigenvectors) in order to formulate the transfer functions of most interest from specific input and output nodes in the FEM model to perform the necessary jitter analysis. The analysts will make assumptions for a range of damping values, and test the sensitivity of the system response to values within the range. As previously mentioned it is not uncommon to use damping values in the range of 0.5% to 0.25% for jitter analysis.

In the low-frequency region the observatory-level FEM is able to predict overall structural behavior with high confidence. However, it is well known that the FEM's prediction accuracy generally decreases as frequency increases. Broadly speaking this increasing uncertainty is typically more apparent in the modal amplitude predictions rather than in the predictions of modal frequencies. The reasons for this can be computational in nature and linked to the mathematical modeling techniques used. The loss of FEM accuracy could also be due to more physical causes. For example, the accuracy of the observatory-level structural FEM will rely heavily on the quality and realism of the assumptions made in the model for sub-assembly and sub-component interfaces and interconnection boundary conditions. Understanding and establishing the physically correct mechanical impedances between the various structural elements is a critical modeling task upon which overall FEM accuracy is dependent. Ideally, the jitter analyst should understand the uncertainty in the coupling terms used in the FEM to represent joint and hinge type mechanical attachments between the observatory's structural subassemblies. The nature of these coupling terms can strongly influence modal frequency predictions. For example, a "hard" joint stiffness would tend to produce an upper bound on modal frequencies whereas a "soft" joint stiffness would produce a lower bound. The assumptions made by the structural engineer concerning coupling terms in the FEM must be clearly identified and documented for the benefit of the entire jitter team.

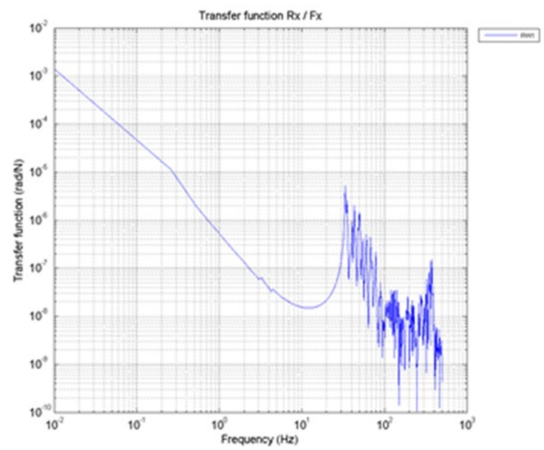


Figure 4. Representative Example of a Structural Transfer Function between a RW Force Component and a Rotational Component of an Instrument LOS (from [36])

The overall uncertainty in the FEM should be quantified by its developers and the frequency beyond which the FEM validity becomes questionable should be established. For example, recall from the discussion of the SOHO micro-vibration problem that the SOHO jitter team was especially interested in obtaining experimental LOS jitter test data at frequencies above 150 Hz as this was the frequency point beyond which the spacecraft FEM was believed lack validity. Early individual modal survey tests of observatory substructures should be considered to anchor the full-up spacecraft structural FEM.

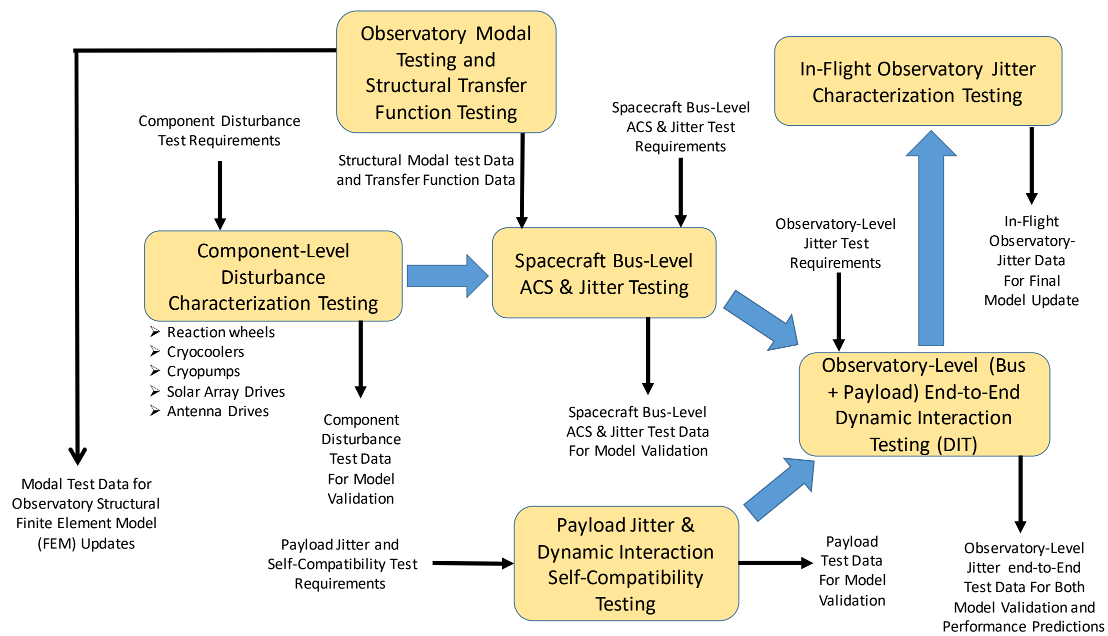
In certain cases, the FEM may require some special "tuning" and adjustments to include more detail than typically found in the structural model typically used for spacecraft loads analyses (see [21] for example). In those cases, it is necessary to accurately predict higher frequency structure vibratory modes with low mass participation which might have a significant impact on jitter but conversely only a negligible impact on loads.

Lastly, the observation can be made that high-fidelity FEMs may not be available early enough to match up schedule-wise with the jitter team's modeling and analysis tasks over the time frame between the project's PDR and CDR. On some projects, this has resulted in the failure to identify serious jitter problems until the CDR milestone was reached. Often the occurrence of jitter-related issues relatively late is caused by the lack of high-fidelity FEMs. Recall, for example, that on the Chandra project a RW imbalance-related disturbance issue, significant enough to require the late inclusion of a RW isolation system, was only discovered at their CDR. It is quite likely that the jitter team will be pressed (and stressed) to provide both system engineering and project management with jitter performance predictions as early as possible with sufficient accuracy on which to base critical decisions regarding the observatory architecture. Steps need to be taken therefore by the jitter team early on in the project lifecycle to communicate their needs for early availability of FEMs with the highest possible fidelity. If these needs are adequately factored into the project planning from the outset, the relationship between the jitter team and the structural modeling team can be better harmonized. Otherwise, the project may find itself with a serious jitter problem at a point in the schedule where recovery/workaround options are very limited and costly.

8. DEALING WITH MODELING UNCERTAINTIES

At the end of the day one of the fundamental risks is that one never really knows if their models are sufficient representations with adequate fidelity to capture the dynamics of the real-world system to be flown. Too much reliance on modeling is not necessarily the soundest approach for mission success, in particular for applications with stringent jitter requirements. A careful balance must be struck between the modeling effort and the physical testing needed to substantiate the models.

High-performance observatories will especially be highly reliant on modeling anchored in test. Comprehensive modeling approaches in which sources of uncertainty are clearly identified, scrupulously quantified, and systematically managed will be needed. High-fidelity testbeds and rigorous testing campaigns spanning the spectrum from component-level tests to payload-level tests to full-up observatory-level tests will be needed to complement the modeling efforts. Figure 5 depicts a recommended jitter testing campaign, spanning an entire project life cycle, starting with component-level disturbance characterization tests and ending with in-flight observatory-level performance testing. The jitter team must take early steps to ensure that project management is made fully aware of these modeling and test needs so that adequate resources can be budgeted, and consistent schedules developed, for all these critically required activities to support high-performance observatory design and development.



The risk of having modeling errors can be greatly mitigated if the project has the luxury of developing a high-fidelity system-level dynamical testbed. Such a Hardware-in-the-Loop system-level testbed allows the micro-vibration team to dramatically and methodically reduce uncertainty in the analytical models. With a system-level testbed, such as the SIM STB3 testbed, anchored with rigorous component-level and subsystem-level test campaigns, the models that fundamentally represent the knowledge of the critical system dynamic interactions can potentially be validated early in the project life cycle prior to the build of the actual flight system.

Probably the single most important step in the overall micro-vibration process is performing a full-up system-level test of the actual observatory on the ground before launch. No surrogates, even high-fidelity well-tuned testbeds, can replace End-to-End testing of the actual 'as built' flight system. In such a system-level test the

RWs should be run, one at a time, over their full operating speed range, while collecting LOS truth data (e.g., instrument-internal servo error signals, if available) along with a comprehensive data set from other instrumentation that can then be used for anchoring models. This type of full-up testing is the most direct and beneficial way of confirming dynamic interactions and obtaining the actual transfer functions. Once the individual RWs are tested other disturbance sources (e.g., SA/HGA drive mechanisms) can then be tested for their impact on jitter. Running a combination of all the disturbance source in a realistic 'day in the life' type test would reveal the overall extent of dynamic interactions on the observatory in the way it will actually operate in-flight.

Ultimately it is only when the system is operating in-flight that one gets sufficient information to determine the adequacy of the pre-launch models. Testing to characterize the observatory's in-flight jitter performance should always be conducted during the commissioning phase as a necessary step to prove pointing/pointing stability requirements are being achieved and to collect truth data for model updates. When planning for the post-launch observatory checkout testing it would highly advantageous to include specific jitter characterization tests that collect sufficient data, for each individual disturbance source, to allow a solid comparison of pre-launch jitter predictions with the actual results seen in-flight. As part of this early in-flight characterization testing any potential operational techniques intended to reduce jitter (e.g., restricted RW speed ranges) can be evaluated for their effectiveness.

An excellent example of this is Landsat-4. Following launch of the Landsat-4 Earth observation spacecraft the team compared Landsat-4 ground-based pre-launch DIT jitter results with the actual jitter levels experienced in-flight. This could be done largely because the Landsat-4 observatory architecture included a high-bandwidth Angular Displacement Sensor (ADS) in the range of 2-18 Hz to directly measure in-orbit high-frequency angular motions that were well outside the lower bandwidth of the spacecraft's ACS gyros. In effect, this was an opportunity for the in-flight validation of the disturbance models. Reference [57] describes how in-flight measurements of the Landsat-4 Thematic Mapper (TM) instrument scan mirror dynamic disturbances were obtained and presents the outcomes of the comparative analysis.

9. OPTIONS FOR IMPROVING INSTRUMENT LOS JITTER PERFORMANCE

It is not uncommon for the preliminary jitter analysis done early on in a spacecraft development lifecycle to reveal that the predicted instrument LOS errors do not satisfy the science requirements for image data quality. There is a wide range of Observatory-level architectural options to address and mitigate the micro-vibration problem. Specific architectural selections will be driven by mission requirements, modeling capabilities, integration complexity, Size, Weight and Power (SWaP) trades, technology readiness and of course, affordability.

Determining the optimal observatory architecture, from a micro-vibrations viewpoint, will also depend heavily on good communications across the entire mission team. The multi-disciplinary nature of micro-vibrations engineering dictates close technical communications and technical interactions primarily between the spacecraft structural dynamics engineers, mechanical systems engineers, attitude control engineers and flight software developers. In some cases, the payload sensor engineers as well as payload sensor ground-based data (i.e., science image data) processing engineers can also be engaged in solving the micro-vibration problem should out-of-specification issue present themselves.

At the system-level (i.e., Observatory plus Ground Segment), there exist several different potential solutions for improving out-of-specification instrument LOS jitter issues. Figure 6 illustrates a number of possible options for improving Instrument LOS Jitter Performance. As described below these options range from relatively simple operational fixes such as constraining the in-flight RW speeds to incorporating relatively complex (and costly) active isolation on-board the observatory.

If the preliminary micro-vibration/LOS jitter analysis results indicate performance requirement shortfalls then various approaches to achieving sufficient micro-vibration management improvements can be assessed to correct the problem. Such potential options include: 1) reduction of the particular internal disturbance of concern that is exciting the LOS jitter at its source (e.g., obtaining a 'quieter' RW or implementing ways to quiet the existing RW, or obtaining a mechanically 'quieter' cryocooler, etc.), 2) localized stiffening of the spacecraft bus structure (or the payload instrument mounting structure) to move the resonant frequency away from the frequency of the disturbance input, 3) active or passive isolation (i.e., mechanical filtering) of the disturbance source, 4) isolation of the particular sensitive payload sensor, and/or 5) complete isolation of the entire payload module itself from the spacecraft bus containing the disturbance sources of concern. Detailed trade analyses will likely need to be performed in order to make decisions as to which option is the most attractive from a system perspective. The optimal solution could possibly be a combination of these improvement options.

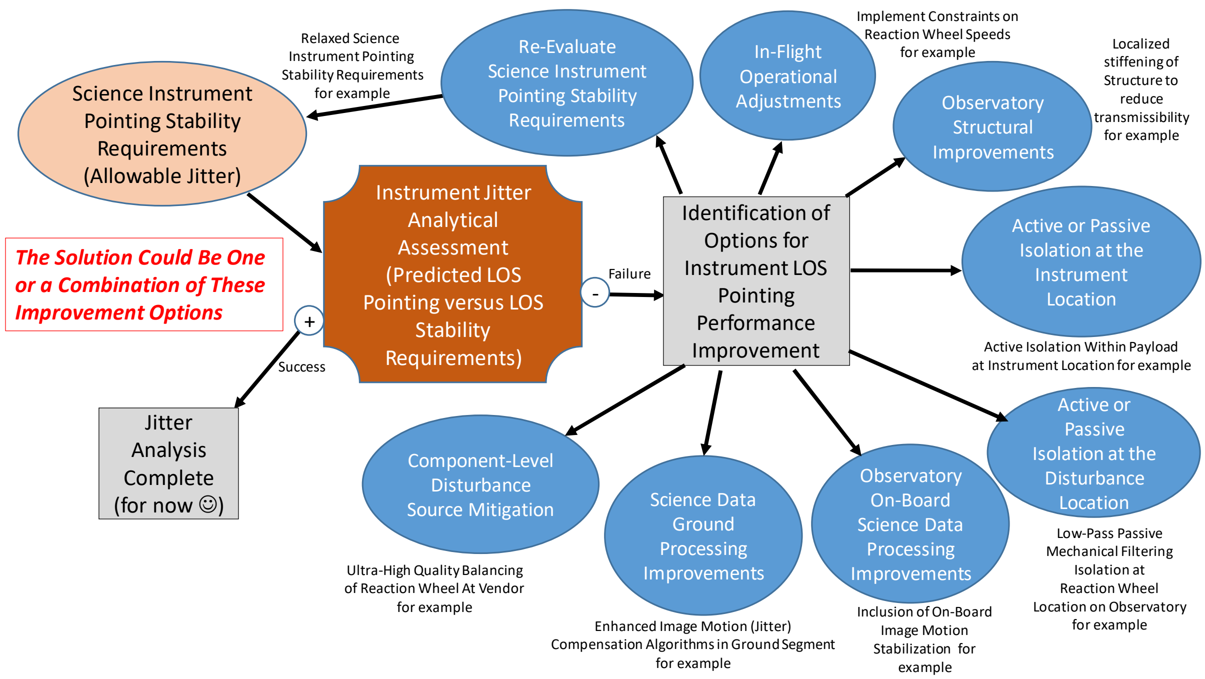


Figure 6. Possible Options for Improving Instrument LOS Jitter Performance

10. STRUCTURAL IMPROVEMENTS

Micro-vibration can be partially managed along the Observatory's structural transmission path, from the location of an individual disturbance source to a point of interest within the science payload, through judicious alterations to the structure. This custom tailoring of the structure may take the form of changing either the primary structure and/or certain relevant secondary structural components such as a RW mounting bracket. This involves adding localized stiffening materials to specific structural locations to attenuate disturbance transmission to the sensitive instrument at a specific frequency of vibration. Stiffening has the effect of moving the vibration mode to a higher frequency sufficiently far away from the instrument's susceptible frequency. Obviously, there will be a resulting mass penalty incurred when adopting this approach. Observatory mass constraints may limit the effectiveness of this approach and, if adopted, some level of additional structural testing will likely be needed to verify the desired change in structural stiffness.

11. COMPONENT-LEVEL DISTURBANCE SOURCE MITIGATIONS

One technique here is to task the RW vendor to perform specialized testing to perform mission-unique ultra-fine balancing of the observatory's RWs. These special wheel balancing tests will undoubtedly add cost at the component-level but this could be money well spent if it reduces expensive testing and analysis later in the mission development process at the observatory level. In some very stringent mission applications it may be necessary to "cherry pick" the individual flight RWs based upon their measured disturbance data.

12. ISOLATION

Micro-vibration can also be partially managed with the incorporation of passive and/or active isolation systems. For example, as is being done on NASA's JWST, RWs can be mounted on a passive vibration isolation mount which itself is attached the vehicle's primary structure. This type of passive isolator effectively serves as a mechanical low-pass filter, which attenuates the transmission of high-frequency RW disturbances to the science payload. There are multiple passive isolation system concept implementation alternatives such as springs with fluid damping, flexures with sandwiched viscous-elastic materials, and simply systems reliant on elastomeric materials.

There is a rich technical literature base associated with spacecraft passive and active isolation technology and engineering (see for example [58-70]). It is worth noting that in the recent past there has been some promising research and development in the area of hybrid systems combining both passive and active isolation technology (see [70]).

One point we wish to make is that isolation in itself is not a panacea and the use of either passive or active isolation needs to be carefully considered from multiple perspectives.

While passive isolation systems are typically much less complex and less costly than active isolation systems they have some inherent performance limitations. One such limitation is that passive isolation provides no vibration suppression in the low frequency regime below its rolloff (i.e., break) frequency. Also, the rolloff frequency of a passive isolation device cannot be set too low or it will interfere with the functioning of the ACS in the case where the isolated component is an attitude control actuator such as a RW. A recommended practice is to avoid setting the resonant frequency of a passive system below 10 Hz when it is being used to isolate RWs [70]. Another issue is the fact that there is going to be some resonant peaking (amplification) of the passive system before its frequency amplitude response rolls off and disturbance attenuation occurs. Lastly, a byproduct of employing passive isolation is that it can introduce new secondary modes in the system that must in turn be dealt with by the jitter team. So on balance passive isolation solutions may have limited effectiveness for high-performance missions. This would be particularly true if the disturbances tones are harmonic in nature and possess a broadband frequency content such as those generated by RWs and cryocoolers (see [67].

While there are many technology studies and in-depth analyses of active isolation systems for controlling spacecraft micro-vibrations the authors could not identify in the open literature an actual NASA or ESA observatory that employs such active isolation. However, it is clear that active isolation systems are capable of accomplishing high levels of vibration suppression at high frequency while, in most cases, simultaneously avoiding a large resonant peaking effect. However, this performance comes at some cost. Active isolation systems will typically present an unfavorable SWaP trade when compared to passive isolators but will conversely offer much higher levels of vibration suppression/active modal damping relative to passive isolators. Clearly, the active systems are more expensive to acquire than passive systems and will, by definition, require power as well as command/telemetry electrical harnessing to operate. The high-frequency stability and performance of the electro-mechanical feedback control loop at the heart of any active isolation system would need to be investigated. One must also consider the degree to which their use introduces complexity into the observatory's control system architecture. One of the fundamental risks associated with active isolation is that any failures, either due to exposure to the launch environment shock and vibration or to in-flight electronics anomalies, can directly result in mission termination. The Technology Readiness Level (TRL) of an active isolation system, especially in the control electronics components, would have to be rigorously evaluated and the risks of any remaining technology development assessed as critical steps of a project's decision making process to include such active isolation technology on the observatory. Lastly, the project must factor in the fact that an active system will typically have less inherent reliability than the simple passive systems.

13. SCIENCE DATA GROUND PROCESSING IMPROVEMENTS

Another option to mitigate micro-vibration is to compensate for it by making improvements in the ground-based science data processing segment of the overall mission system architecture.

14. ON-BOARD IMAGE STABILIZATION

For some missions employing very high-performance optical sensing payloads the inclusion of on an on-board image stabilization system may serve as the best overall solution to the micro-vibration problem even when considering its relative hardware/software complexity and cost. An example of this is the Image Motion Compensation (IMC) approach used on the GOES-16 meteorological observatory and the ISS employed on SDO. Another more straightforward example is using a fast (high-bandwidth) steering mirror to correct LOS error in an instrument's optical train.

15. OPERATIONAL IMPROVEMENTS

Often, several of the observatory's sources of disturbance can be operationally manipulated in-flight to be less of a jitter inducing threat. The observatory can be 'quieted' by turning some types of equipment off, altering equipment functional modes, limiting operations ranges, and/or changing equipment duty cycles, etc. For example, operators of an observatory can manage the deleterious impact of RW-generated micro-vibration disturbances by constraining wheel speeds to stay within an analytically prescribed range to avoid exciting known structural resonances. The clear advantage of operational techniques is that absolutely nothing need be done physically at the observatory-level. This operational approach to mitigate micro-vibrations conceivably could be extended to carefully manage the reference frequency speed at which other cyclic disturbance sources, such as cryocoolers, operate at in-flight. Flying a cryocooler with a set of discrete operational frequencies that can be selected inflight provide operational flexibility for jitter mitigation. Another clever example of a technique to limit jitter disturbances operationally is to randomize the stepping of the SA drive mechanism so as to effectively spread out the disturbance energy input into the structure.

16. ADVANCED OBSERVATORY ARCHITECTURES FOR DISTURBANCE-FREE PAYLOAD OPERATIONS

There are also advanced alternative observatory architectural options not identified or discussed above which could have significant impact.

For example, one architectural approach to lowering an observatory's disturbances might entail simply doing away with RWs for precision attitude control during science data-taking observational periods and instead relying on Micro Cold Gas (MCG) thrusters for precision attitude control. In this ACS control concept a set of RWs would be used to perform Observatory large-angle attitude slews but would then be powered off during science data-taking periods in which the MCG thrusters would precisely stabilize the vehicle. Such an architecture would have the benefit of eliminating the need for RW disturbance isolation and all that brings with it. Consider that the resulting system would be stiffer without the RW isolation system. In addition, the micro-vibration analysis burden would be reduced for the jitter team. A number of science missions have already employed this type of "reaction wheel-less" form of precision attitude control. On ESA's Gaia spacecraft a set of 12 MCG thrusters are used for fine attitude pointing and spin rate management (see [71]). The MCG thrusters on Gaia use high-pressure nitrogen propellant to generate very small impulses over a thrust range of 1-500 Micro-Newtons.

On ESA's LISA Pathfinder mission the propulsion system of the LISA Technology Package consists of MCG micro-Newton nitrogen thrusters that are based upon those originally developed for Gaia mission [72]. LISA's Drag-Free Propulsion System counteracts the disturbance forces and torques applied on the spacecraft in order to maintain the free-floating (or "free-fall") conditions on the science payload's enclosed master test proof mass. In order to counteract the continuously changing disturbance forces, the thrusters must be able to deliver a continuously modulated thrust between minimum and maximum force (in the range 1 μN to 100 μN) with a response time better than the control system's command frequency (10 Hz). Effectively, the MCG nitrogen thrusters are used on LISA as ultra-precise proportional actuators continuously fired throughout the mission.

An even more extreme, perhaps ultimate, form of observatory disturbance isolation would be to employ the so-called Agile Disturbance Free concept in which the payload and the spacecraft bus are actually separate bodies that would operate individually in close-proximity formation flight [73]. This advanced alternative science observatory architecture, described in detail in [73], could conceivably provide a solution to the combined problems mission architects face of accomplishing agile payload pointing while achieving a disturbance-free payload environment fully isolated from spacecraft bus vibrations. Adopting this close-proximity formation flying observatory architectural concept could possibly yield superior "slew and settle" performance allowing the recovery of stringent pointing control and stability following rapid payload re-orientations while simultaneously permitting uninterrupted science data collection during momentum unloading thruster firings on the de-coupled bus portion of the observatory.

17. SPACECRAFT MICRO-VIBRATION LESSONS LEARNED

Within the broad aerospace community, the importance and value of identifying, documenting, and widely sharing lessons learned is now broadly acknowledged. However, significant lessons learned on a project often are not captured even though they are well known, highly specialized, 'tribal knowledge' amongst the project team members. Documenting and sharing lessons learned helps engineers and managers to minimize project risk and improve performance of their systems. In the authors' view leveraging lessons learned is especially valuable on new system development projects to help overcome the team's unfamiliarity with previously identified technical pitfalls and challenges. It is in that spirit that we informally offer the following lessons learned from our experiences working spacecraft micro-vibration problems:

1. Micro-vibrations can affect any design, but the impacts are not all the same

2. Just because micro-vibration requirements are easy or nonexistent for a given design, it does not mean they won't play a role in performance

3. When micro-vibration related requirements are challenging, iterating on system architectures with adequate model fidelity is paramount to selecting the right architecture

4. The more challenging a micro-vibrations related set of requirements, the higher the need for model fidelity at the start of a project

5. There is no substitute for early sensitivity analysis especially when coupled to a complete error budget

6. A complete error budget is absolutely needed at the start of a project with challenging micro-vibration requirements

7. It is paramount to identify all possible sources of error early in the design cycle. Do this even if quantification is not easy or their effect is perceived to be inconsequential

8. Micro-vibrations are a system level problem. This is one case where truly all aspects of a system design strongly couple and challenge the typical subsystem design. The tougher the requirement the stronger the inter-subsystem dependencies and the harder it is to solve the problem within the domain of a single subsystem. In the limit, the toughest micro-vibration problems require a system level team that encompasses all sub-systems. JPL calls this team the Dynamics and Controls team, separate from the GN&C, Mechanical, /Instrument, Navigation and Ground teams.

9. The more challenging micro-vibrations problems require larger and more technical teams. Project

management should therefore plan and budget appropriately the necessary team resources.

10. The team tackling the micro-vibrations related requirements works best when it can clearly decompose the design job among the classical subsystems in a project, while taking on the task of validating this decomposition and owning the observatory's micro-vibrations related requirements Verification and Validation (V&V). This team must make sure it can model the nuances that will inevitably come with this decomposition

11. The team tackling the micro-vibrations must start its work early in the project design cycle and must endeavor to understand the nuances of the decomposition of its work into individual subsystem requirements as early as possible. However, as the system design progresses it is quite likely that new requirements on the subsystems will be needed to deal with the nuances discussed above

12. The team working on the micro-vibration related requirements for the project will very likely drive the system level design, architecture, testing and thus the project cost/schedule, hence it must be prepared to constantly communicate its results, solutions, strategies, and architecture to get the project, system and subsystem's buy-in on them. Yes, communication is very important or the subsystems will not design to meet the jitter team's requirements.

13. Yes, micro-vibrations couple the subsystems; however, this is not a license to come up with complex designs. It is always best to keep the solutions simple even if that means over-achieving. Operational simplicity and flight heritage must always be kept in mind.

14. Keep the on-board calibrations and alignments for challenging micro-vibration problems in front of the micro-vibrations team to ensure the errors and nuances associated with these errors are not omitted until it is too late.

15. Incremental piecewise testing to inform and anchor the model, reducing system performance risk, is critically important for many missions.

16. A solid observatory system-level jitter test is the best way to gain confidence in an End-to-End model and performance predictions, and tests can be valuable for a range of configurations, some with minimal impact to existing observatory test plans.

18. THE ROAD AHEAD

Looking forward here are some ideas born from years of experience working to solve spacecraft micro-vibration problems and working a number of 'different flavors' in the micro-vibrations arena:

1. There is a need for a well thought out distributed sensing system that could be used to collect data on the performance of a flight system against its micro-vibration requirements. For example, laser-based metrology or accelerometers could be used in a distributed fashion to capture the motion of key optical elements in a telescope.

2. SIM used distributed laser metrology systems to control the path traveled by starlight inside its complex instrument. This allowed control of the internal dynamics where it really mattered and reduced the need for bandwidth in the fine guidance sensors. Direct measurement of the optical path of a complex telescope-like instrument can mitigate the need for higher fidelity modeling by enabling broadband control of the micro-vibrations.

3. "Test as you fly" V&V campaigns for systems with challenging micro-vibration requirements are very expensive and can be close to impossible to execute for large distributed systems. This implies the need for higher fidelity models that need to be V&V'ed by CDR prior to implementation! We need to invest in improving the early fidelity of models especially at frequencies between 50 and 500 Hz.

4. There is a need to develop better isolators for RWs and MWs for applications that need agility, e.g. non-contact isolators or dual mode isolators

5.There is a need to develop and flight qualify micro-Newton class thrusters, paying attention to reliability, configurability of thrust output (minimum thrust and Minimum Impulse Bit or MIB) and lifetime issues. As serviceability becomes more mainstream, refueling micro-thruster tanks can clearly extend mission life. Early studies show that for L2 orbits propellant needs are not prohibitive. The benefits of micro-thrusters include the possible elimination of isolation, and less reliance on high fidelity broad band models as is now the case.

6. Dual use of on-board structures is risky but could be developed in the case of large components like the SAs to provide slew agility to systems with micro-thrusters in exchange for small SA slews. (The larger the ratio of the SA inertia to the spacecraft inertia the smaller the SA motion).

7. Testing of disturbances is typically an up-hill battle on projects with challenging micro-vibration requirements. Dedicated specialized test facilities may not be available when needed. Obtaining, early in the project life cycle, Engineering Models (EMs) of components are also needed to characterize the effect of such disturbances. Special care must be taken to ensure that these EMs faithfully represent the flight hardware. This type of testing will make a world of difference in the uncertainty of the design and the uncertainty of the performance of the system.

8. Passive isolation has reached a wall in that dual stages of isolation are hard to extend. There is clearly a need to develop active isolation systems that can gracefully degrade to passive isolators so as to not interfere with the on-board ACS. Reliability of active RW isolators and the possibility that their failure could lead to general ACS failure and end of mission is a common reason for excluding them from architectures.

9. Adding funds to a challenging project like WFIRST to enable it to add a distributed sensing system should be considered. The inclusion of a laser metrology system, or micro-g class accelerometers, comes immediately to mind, either of which would allow the continuous collection of relevant micro-vibration data for ground harvesting and analysis.

19. CLOSING THOUGHTS

The critical imperative, in today's micro-vibration paradigm, of conducting micro-vibration/jitter tests at the integrated system level in order to assess end-to-end micro-vibrations susceptibility/performance should be evident to the reader. One key aspect of this is the degree of difficulty encountered when attempting to adequately perform ground testing on full-up integrated spacecraft systems prior to launch. For some high-performance space systems, it may prove to be extremely difficult and very costly, if not physically impossible, to perform testing to fully validate analytical predictions of micro-vibration behaviors and to build confidence that LOS jitter performance requirements will be satisfied in-flight. This testing difficulty is primarily due to the 1-g gravity effects and cultural/environment noise levels in the ground test facilities.

Fortunately, less ideal system level tests can still provide invaluable information to anchor models (by modeling the test's boundary conditions). Even hard mounted 'fixed-base' ground tests can produce good higher frequency transfer functions and jitter measurements, which is, as mentioned earlier, an area of greater FEM uncertainty. Programs and projects should supplement their model-based knowledge of performance by placing an emphasis on a rigorous campaign of in-flight micro-vibration testing during the early-orbit commissioning phase. For Programs (with a series of multiple similar missions), a dedicated instrumentation package should be flown on the initial 'first-of-a-kind' observatory to better characterize performance allowing for modifications and tuning for subsequent observatory builds in the series.

Increasing an in-flight emphasis for the ultimate validation of pre-launch modeling adequacy and to update system performance predictions, and improve the community's knowledge base will likely drive the need for developing new advanced technology types of test instrumentation. These might include such technologies as wireless force/torque/stress/strain transducers embedded in the spacecraft structure. The other consequence of evolving the micro-vibration test paradigm from the traditional ground test and analysis to an in-flight regime is that new capabilities for spacecraft (including the payload) reconfiguration may need to be developed and implemented in order to be able to adjust system performance if the in-flight measured micro-vibration levels exceed pre-launch model predictions.

20. SUMMARY CONCLUSIONS

Looking forward one can identify the clear trends within both NASA and ESA towards planning technically aggressive spaceflight missions that include ultra-performance optical payloads with delicate highly vibration-sensitive scientific/observational instruments. For example, extremely formidable and challenging micro-vibration engineering problems lie ahead for NASA in the near-term in the form of WFIRST-CGI and, further down the road, for the potential HabEx and LUVOIR missions~~s~~. One can foresee that multiple micro-vibration engineering and technology risk areas will obviously need to be mitigated.

To successfully meet these future challenges NASA and ESA will need to leverage and build upon their collective past experiences in addressing micro-vibration problems. Looking back one sees that both NASA and ESA, together with our industry partners, have a long, technically rich, and impressive history of solving the difficult engineering problems associated with managing, controlling, and testing spacecraft micro-vibrations. Our experiences in dealing with undesirable jitter perturbing payload instrument pointing/pointing stability have taught us the imperative of focusing on and making critical architectural decisions early on in the process.

When micro-vibration related requirements are challenging, iterating on system architectures with adequate model fidelity is paramount in the overall process of judiciously selecting the right observatory architecture. Architectural decisions concerning micro-vibration made early in a project's lifecycle, and the decisions not made as well, always have long-term mission consequences and ramifications, both good and bad. The multi-disciplinary jitter team tackling the micro-vibration problem must start its work early in the project design cycle and must endeavor to understand the nuances of its work decomposing observatory-level requirements into subsystem requirements as early as possible.

In this paper, the authors have attempted to share their subject matter knowledge and their perspectives on spacecraft micro-vibrations. It was pointed out that before starting the design process a jitter analyst should recognize and understand that not all observatory designs require the same level of care and attention when it comes to solving the micro-vibration problem. The design process is of course iterative, but one must start a new design somewhere. The authors provided some of their recommended rules of thumb to provide some guidance on where to initiate and how to approach a new micro-vibration design challenge. The authors presented a set of micro-vibration lessons learned that we believe are valuable, worth sharing with the community, and which can be leveraged on new system development projects to help overcome the team's unfamiliarity with previously identified micro-vibration technical pitfalls and challenges.

21. ACKNOWLEDGMENTS

The authors would like to thank their colleagues at both GSFC and at JPL for the thoughtful inputs and suggestions to improve the quality of this survey paper. The authors also express their gratitude to Michael Hagopian (Sigma Space Corporation), to Aron Wolf (JPL), and also to Milan Mandic (JPL) for their thorough and detailed peer review of this paper. NESC management is to be acknowledged as well for sponsoring the creation of this paper as a NESC GN&C Technical Discipline Team 'knowledge capture' product. Lastly, we would be remiss if we did not extend our acknowledgments and heartfelt thanks to Erin Moran and Dee Bullock at NESC/NASA Langley Research Center for their support in preparing this paper for publication. Part of this work described here was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA. A decision to implement the WFIRST, HabEx, or LUVOIR missions will not be finalized until NASA's completion of the National Environmental Policy Act (NEPA) process for each. The information provided in this document is being made available for planning and information purposes only.

22. REFERENCES

1. European Space Agency, European Cooperation for Space Standardization (ESA ECSS) (2012), Section 13.3 Micro-vibrations, Space Engineering: Spacecraft Mechanical Loads Analysis Handbook, ECSS-E-HB-32-26.

2. Addari, D., (2016), A Semi-Empirical Approach for the Modelling and Analysis of Microvibration Sources On-Board Spacecraft, Chapter 2, PhD Thesis, University of Surrey.

3. Kamiya, T., et. al. (2004), Microvibration Management and Pointing Stability Analysis of SELENE Satellite, *IFAC Automatic Control in Aerospace*, Saint-Petersburg, Russia.

4. Yoshida, N., et al. (2013), Spacecraft with Very High Pointing Stability: Experiences and Lessons Learned, *IFAC Proceedings* Volume 46, Issue 19, 2013, Pages 547-552, 19th IFAC Symposium on Automatic Control in Aerospace, 2-6 September 2013, Würzburg, Germany.

5. Dougherty, H. J., et. al. (1982), Space Telescope Pointing System, *Journal of Guidance, Control, and Dynamics*, Vol. 5, No. 4, 1982, pp. 403-409

6. Dougherty, H. J., Rodoni, C., Rodden, J., & Tompetrini, K. (1983), Space Telescope Pointing Control", AAS/AIAA Paper 83-365, *Astrodynamics*, Volume 54 1 & 11, Advances In The Aeronautical Sciences, 1983.

7. Nurre, G. S. & Dougherty, H. J. (1984), *The Pointing System for Space Telescope, The National Symposium and Workshop on Optical Platforms*, Charles L. Wyman, editor, Proceedings of SPIE, vol. 493, Society of Photo-Optical Instrumentation Engineers, Bellingham, WA.

8. Beals, G. A., et. al. (1986), Space Telescope Precision Pointing Control System, AIAA Technical Paper 86-1981, *AIAA Guidance, Navigation, and Control Conference Proceedings*.

9. Hasha, M. D. (2016), High-Performance Reaction Wheel Optimization for Fine-Pointing Space Platforms: Minimizing Induced Vibration Effects on Jitter Performance plus Lessons Learned from Hubble Space Telescope for Current and Future Spacecraft Applications, *Proceedings of the 43rd Aerospace Mechanisms Symposium*, NASA Ames Research Center, 4-6 May 2016.

10. Nurre, G. S., Sharkey, J. P., & Waites, H. B. (1991), Initial Performance Improvement Due to Design Modifications for the Pointing Control System on the Hubble Space Telescope, *AAS Paper 91-071, Proceedings of the 14th Annual American Astronomical Society (AAS) Guidance and Control Conference*, Keystone, CO, February 1991.

11. Vadlamudi, N., Blair, M. A., & Clapp, B. R. (1992), Hubble Space Telescope On-Orbit Transfer Function Test, AIAA Paper 92-4614, *Proceedings of the AIAA Guidance, Navigation, and Control Conference*, Hilton Head Island, South Carolina, United States, August 1992.

12. Sharkey, J. P., Nurre, G. S., Beals, G. A., & Nelson, J. D. (1992), A Chronology of the On-Orbit Pointing Control System Changes on the Hubble Space Telescope and Associated Pointing Improvements, *AIAA Paper 92-4618, AIAA Guidance, Navigation and Control Conference*, 10-12 August 1992, Hilton Head Island, South Carolina, United States.

13. Nurre, G. S., et. al. (1993), Design and Performance of the Currently Flying HST Pointing Control System, *AAS Paper 93-002, Proceedings of the 16th Annual AAS Guidance and Control Conference*, Keystone, CO, February 1993.

14. C. L. Foster, Tinker, M. L., Nurre, G. S., & Till, W. A. (1995), *The Solar Array-Induced Disturbance of*

the Hubble Space Telescope Pointing System, NASA TP-3556, May 1995.

15. Jedrich, N., et. al. (2002), Cryo Cooler Induced Micro Vibration Disturbances to Hubble Space Telescope, *SPIE* (NASA Tech Doc N20020060462).

16. Clapp, B. R., Sills, J. W., & Voorhees, C. (2002), Hubble Space Telescope Pointing Performance Due to Micro-Dynamic Disturbances from the NICMOS Cyrogenic Cooler, AIAA 2002-1249, *43rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, 22-25 April 2002, Denver, Colorado, United States.

17. Schauwecker, C J., et. al. (1997), Imaging Pointing Control and Aspect Determination System for the NASA Advanced X-Ray Astrophysics Facility, *Proceedings of the Annual AAS Rocky Mountain Guidance and Control Conference*, AAS 97-04, pp. 233-249, 1997.

18. Pendergast, K. J., & Schauwecker, C. J. (1998), Use of a Passive Reaction Wheel Jitter Isolation System to Meet the Advanced X-Ray Astrophysics Facility Imaging Performance Requirements, NASA CR-1998-207926, *Astronomical Telescope and Instrumentation Conference, International Society for Optical Engineering*, 20-28 March 1998; Kona, Hawaii, United States.

19. Starin, S. R., et al. (2005), Attitude Control System Design for the Solar Dynamics Observatory, NASA/GSFC Code 595 F*light Mechanics Symposium*, 18-20 October 2005, Greenbelt, Maryland, United States.

20. Liu, Kuo-Chia, & Andrews, S. (2003), SDO Jitter Analysis Approach, NASA/GSFC/Code 595 Briefing, 21 August 2003, https://femci.gsfc.nasa.gov/presentations/Liu_JitterAnalysisApproach.pdf.

21. Liu, Kuo-Chia, et al. (2005), Dynamic Jitter Modeling and Analysis of Solar Dynamic Observatory, *Flight Mechanics Symposium*, NASA Goddard Space Flight Center, Greenbelt, Maryland, United States, October2005.

22. Bourkland, K. L., Liu, Kuo-Chia, & Blaurock, C. (2007) A Jitter-Mitigating High Gain Antenna Pointing Algorithm for the Solar Dynamics Observatory, *Proceedings of the 20th International Symposium on Space Flight Dynamics*, (NASA/CP-2007-214158), September 2007, Greenbelt, Maryland, United States.

23. Liu, Kuo-Chia, et al. (2007), Jitter Test Program and On-Orbit Mitigation Strategies for Solar Dynamic Observatory, *Proceedings of the 20th International Symposium on Space Flight Dynamics*, (NASA/CP-2007-214158), September 2007, Greenbelt, Maryland, United States.

24. Laurens, P., Decoux, E., & Janvier, M. (1996), SOHO Microvibrations: Analyses, Tests and Flight Results, Proceedings of the **3rd ESA International Conference on Spacecraft Guidance, Navigation and Control Systems**, ESA SP-381, 1997, ESA/ ESTEC, Noordwijk, the Netherlands, p.489, 26-29 November 1996.

25. Meza, Luis, et. al. (2005), Line of Sight Stabilization of James Webb Space Telescope, AAS Paper 05-002, *27th Annual AAS Guidance and Control Conference*, 5-9 February 2005, Breckenridge, Colorado, United States.

26. Chapel, J., Stancliffe, D., Bevacqua, T., Winkler, S., et al. (2014), Guidance, Navigation, and Control Performance for the GOES-R Spacecraft, *Proceedings of the 9th International ESA Conference on Guidance, Navigation & Control Systems*, June 2014, Porto, Portugal.

27. Davis, L. P., D.R. Carter, D. R., & Hyde, T. T. (1995), Second-Generation Hybrid D-Strut, *Proceedings SPIE* Vol. 2445, Smart Structures and Materials 1995: Passive Damping, pp. 161-175, May 1995.

28. Freesland, D., Carter, D., Chapel, J., et al. (2015), GOES-R Dual Isolation, the 3*8th Annual AAS Rocky Mountain Section Guidance and Control Conference*, January 2015.

29. Carter, D., Clapp, et al. (2017), GOES-16 On-Orbit Dual Isolation Performance Characterization Results, *Proceedings of the 10th International ESA Conference on Guidance, Navigation & Control Systems*, 29 May – 2 June 2017, Salzburg, Austria.

30. Liu, K. & Blaurock, C. (2017), Wide-Field Infrared Survey Telescope (WFIRST) Integrated Modeling, Presentation by GSFC's WFIRST Integrated Modeling Team, *NASA Telescope Stability Workshop*, Boulder, Colorado, United States, 4 October 2017.

31. Laskin, R. A. (2000), Technology Development for the Space Interferometry Mission (SIM) - Status and Plans, *2001 IEEE Aerospace Conference*, Big Sky, Montana, United States, 10 March 2000.

32. Alvarez-Salazar, O. S., Renaud, G., & Azizi, A. (2004), Space Interferometry System Testbed-3: Architecture, *IEEE Aerospace Conference*, Big Sky, Montana, United States, 6 March 2004.

33. Dekens, F. G., Alvarez-Salazar, O. A., Azizi, A., et. al. (2004), Kite: Status of the External Metrology Testbed for SIM, *SPIE Conference on Astronomical Telescopes and Instrumentation*, Glasgow, Scotland, 21-25 June 2004.

34. Fischer, J., Alvarez-Salazar, O. A., Azizi, A., & Sun, G. (2005), Dim Star Fringe Tracking Demonstration on SIM's System Testbed-3 (STB3), *IEEE Aerospace Conference*, Big Sky, Montana, United States, 4-11 March 2005.

35. Vitelli, M., Specht, B., & Boquet, F. (2010), A Process to Verify the Microvibration and Pointing Stability Requirements for the BepiColumbo Mission, I*nternational Workshop on Instrumentation for Planetary Missions (IPM-2012)*, Greenbelt, Maryland, 10-12 October 2012.

36. Tanguy, P. (2011), MTG Microvibration Requirements and Associated Potential Impact on the Satellite Design, *Paper AAS 11-062, Proceedings of the 34th Annual AAS Rocky Mountain Section Guidance and Control Conference*, February 2011.

37. Bialke, B. (1996), Microvibration Disturbance Sources in Reaction Wheels and Momentum Wheels, *Proceedings of the European Conference on Spacecraft Structures, Materials & Mechanical Testing*, Noordwijk, the Netherlands.

38. Bialke, B., A Compilation of Reaction Wheel Induced Spacecraft Disturbances, AAS paper 97-038, *20th Annual American Aeronautical Society (AAS) Guidance and Control Conference.*

39. Bialke, B., High Fidelity Mathematical Modeling of Reaction Wheel Performance, AAS paper 98-063, *21th Annual American Aeronautical Society (AAS) Guidance and Control Conference.*

40. Bialke, B. (2011), Microvibration Disturbance Fundamentals for Rotating Mechanisms, AAS paper 11-061, February 2011, *34th Annual American Aeronautical Society (AAS) Guidance and Control Conference.*

41. Laurens, P., & Decoux, E. (1997), Microdynamic Behavior of Momentum and Reaction Wheels, *Proceedings of the Second Space Microdynamics and Accurate Symposium*, Toulouse, France, 1997.

42. Masterson, R. A., Miller, D. W., & Grogan, R. L. (1999), Development of Empirical and Analytical Reaction Wheel Disturbance Models, *Proc. of Structures, Structural Dynamics and Materials Conference*, St. Louis, Missouri, United States, 1999.

43. Masterson, R. A., Miller, D. W., & Grogan, R. L. (2002), Development and Validation of Reaction Wheel Disturbance Models: Empirical Model, *Journal of Sound and Vibration* 249 (2002) 575–598.

44. Oh, S. H., & Rhee, S. W. (2002), Micro-vibration Measurement, Analysis and Attenuation Techniques of Reaction Wheel Assembly in Satellite, *Journal of the Korean Society for Aeronautical & Space Sciences* 30 (8) (2002) 126–132.

45. Heimel, H. (2011), Spacewheel Microvibration — Sources, Appearance, Countermeasures, *Proceedings of the Eighth International ESA Conference on Guidance & Navigation Control Systems*, Karlovy Vary, Czech Republic, 2011.

46. Heimel, H. (1997), The Microvibration Characteristics of Momentum and Reaction Wheels, *Second Space Microdynamics and Accurate Control Symposium (SMACS 2)*, Toulouse, May 1997.

47. Blaurock, C. (2011), Reaction Wheel Disturbance Modeling, AAS Paper 11-063, *34th Annual AAS Guidance and Control Conference*, Breckenridge, Colorado, United States, February 2011.

48. Zhang, Z., Ren, W., & Aglietti, G. S. (2012), Microvibration Modeling, Validation and Coupled Analysis of a Reaction Wheel in Satellite, *Proceedings of the European Conference on Spacecraft Structures, Materials & Environmental Testing*, Noordwijk, the Netherlands, 2012.

49. Le, P. (2017), Micro-disturbances in Reaction Wheels, PhD dissertation, Eindhoven University of Technology, ISBN:978-90-386-4221-5 March 2017.

50. Wagner, M. (2011), ESA's New High Precision Reaction Wheel Characterisation Facility, AAS Paper 11-065, 3*4th Annual AAS Guidance and Control Conference*, Breckenridge, Colorado, United States, February 2011.

51. Wagner, M., Airey, S., Piret, G., & Phuoc, L. (2012), New Reaction Wheel Characterisation Test Facility (RCF), AAS Paper 12-077, *35th Annual AAS Guidance and Control Conference*, Breckenridge, Colorado, USA, February 2012.

52. Ayari, L., et. al. (2016), Testing and Measurement of Mechanism-Induced Disturbances, *Proceedings of the 43rd Aerospace Mechanisms Symposium*, NASA Ames Research Center, 4-6 May 2016.

53. Jarvis, C., Veal, D., Hughes, B., Lovelock, P., & Wagner, M. (2016), 6 Degree of Freedom Microvibration Test Facility for European Space Agency, *14th European Conference on Spacecraft Structures*, Materials and Environmental Testing, ECSSMET 2016.

54. Wismer, S., Messing, R. & Wagner, M. (2017), First Real-Life Results of Novel Micro Vibration Measurement Facility, *Proc. 'ESMATS 2017'*, Univ. of Hertfordshire, Hatfield, U.K., 20–22 September 2017.

55. Jarvis, C., et. al. (2017), A 6-DOF Microvibration Isolation, Measurement and Generation Facility, *Workshop of the Consultative Committee for Acoustics*, Ultrasound and Vibration, Sept. 2017, [https://www.bipm.org/cc/CCAUV/Allowed/11/C-Jarvis-CCAUV-MVMS.pdf.](https://www.bipm.org/cc/CCAUV/Allowed/11/C-Jarvis-CCAUV-MVMS.pdf)

56. An Evaluation of Reaction Wheel Emitted Vibrations for Large Space Telescope, NASA Technical Report N76-18213, January 1976, Sperry Flight Systems (for NASA/Marshall Space Flight Center).

57. J. Sudey, J., & Schulman, J. (1984), In-orbit Measurements of Landsat-4 Thematic Mapper Dynamic Disturbances, IAF paper 84-117, *35th International Astronautical Federation*, International Astronautical Congress, Lausanne, Switzerland, 7-13 October 1984.

58. Rodden, J., et. al. (1986), Line-of-Sight Performance Improvement with Reaction-Wheel Isolation, AAS Paper 86-005, *Proceedings of the Annual Rocky Mountain Guidance and Control Conference*, Keystone, CO, 1-5 February 1986 (A87-32726 13-18), San Diego, CA, Univelt, Inc., 1986, p. 71-84.

59. Defendini, et al. (1999), Technology Predevelopment for Active Control of Vibration & Very High Accuracy Pointing Systems", *4th ESA Spacecraft Guidance, Navigation and Control Systems Conference*, ESA/ESTEC, Noordwijk, The Netherlands, 18-21 October 1999.

60. Maly, J. R., et. al. (1999), Hubble Space Telescope Solar Array Damper, *Proceedings SPIE*, Vol. 3672, pp. 186- 197, 1999.

61. Cobb, R. G., et. al. (1999), Vibration Isolation and Suppression System for Precision Payloads in Space, *Smart Materials and Structures*, Volume 8, Number 6, 1999.

62. Bronowickid, A. J., Abhyankarddag, N. S., & Griffin, S. F. (1999), Active Vibration Control of Large Optical Space Structures, *Smart Materials and Structures*, Volume 8, Number 6, 1999.

63. Vaillon, L., & Philippe, C. (1999), Passive and Active Microvibration Control for Very High Pointing Accuracy Space Systems, *Smart Materials and Structure*, Volume 8, Number 6, pp. 719-728, 1999.

64. Grodsinsky, C. M., & Whorton, M. S. (2000), Survey of Active Vibration Isolation Systems for Microgravity Applications, *Journal of Spacecraft and Rockets*, Vol. 37, No. 5, September-October 2000.

65. A. J. Bronowicki, A. J. (2004), Vibration Isolator for Large Space Telescopes , *45th IAA ASME ASCE AHS ASC Structures, Structural Dynamics & Materials Conference*, 2004, 10.2514/6.2004-1903.

66. Marquardt, E. D., Glaister, G., Marquardt, J. S., Raab, J. & Durand, D. (2013), Testing Results for Low Exported Force and Torque Cryocooler Mounts, *Cryocoolers 17*, ICC Press, Boulder, Colorado, 2013

67. Kamesh, D., Pandiyan, R., & Ghosal, A. (2010), Modelling, Design and Analysis of Low Frequency Platform for Attenuating Micro-Vibration in Spacecraft, *Journal of Sound and Vibration* 329 (17):3431-3450, August 2010

68. Liu, C., et. al. (2015), Recent Advances in Micro-Vibration Isolation, *Mechanical Systems and Signal Processing*, Volumes 56–57, Pages 55-80, May 2015.

69. Flint, E. M., et. al. (2000), Cyrocooler Disturbance Reduction with Single and Multiple Axis Active/Passive Vibration Control Systems, *Proceedings of the SPIE*, Volume 3989, p. 487-498, *SPIE's 7th Annual International Symposium on Smart Structures and Materials*, Newport Beach, California, United States, 2000.

70. Boquet, F., & Malric-Smith, F., J-P. Lejault, J-P. (2011), Active & Passive Microvibration Mitigation System for Earth Observation and Space Science Missions, *34th Annual AAS Guidance and Control Conference*, Breckenridge, Colorado, United States, February 2011.

71. Chapman, P., Colegrove, T., Ecale, E., & Girouart, B. (2011), GAIA Attitude Control Design: Milli-Arcsecond Relative Pointing Performance using Micro-Thrusters and Instrument in the Loop, *8th International ESA Conference on Guidance and Navigation Control Systems*, Karlovy Vary, Czech Republic, June 2011.

72. Armano, M., et. al., A Strategy to Characterize the LISA-Pathfinder Cold Gas Thruster System, *Journal of Physics: Conference Series*, Volume 610, conference 1.

73. Pedreiro, N. (2005), Agile Disturbance-Free Payload, *AIAA Guidance, Navigation, and Control Conference and Exhibit*, San Francisco, California, United States, 15 - 18 August 2005.